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The analysis shows that the cource control approach to water quality management is currently feasible. Institutions to implement such an approach on agricultural lands already exist. Economic and physical models are readily available for use under this approach.

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TOWARD INSTREAM WATER-QUALITY MANAGEMENT

by

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Contract Number 68-03-2597

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FOREWORD

As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient management tools based on greater knowledge of the environmental phenomena to be managed. As part of this Laboratory's research on the occurrence, movement, transformation, impact and control of environmental contaminants, the Technology Development and Applications Branch develops management and engineering tools to help pollution control officials achieve water quality goals through watershed management.

Agricultural sources contribute significantly to water pollution problems in many areas of the United States. This report describes part of a 2-year study in which the social, economic, legal and institutional issues involved in the management and control of pollutants from agricultural nonpoint sources were examined.

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This report compares two approaches to the agricultural nonpoint source pollution control problem: source control and instream water quality management (ISWQM). Source control is a strategy of controlling pollution loadings by using standards such as soil loss limits or best management practices (BMPs) without relating them directly to water quality goals. ISWQM is a strategy of determining water quality goals by examining pollution effects and other considerations and developing a resource management plan for achieving those goals. ISWQM relates land management more closely to water quality goals. The report discusses the informational needs, institutional arrangements, and the strengths and weaknesses of each approach and suggests some intermediate alternatives that could be explored. Various physical, planning and decision-making models that could be utilized under the two approaches are analyzed.

The analysis shows that the source control approach to water quality management is currently feasible. Institutions to implement such an approach on agricultural lands already exist. Economic and physical models are readily available for use under this approach. A number of institutional changes, however, could be made to more effectively implement this approach. ISWQM encounters more problems than source control because of greater informational costs, technical problems and political resistance. ISWQM has the capability, however, to define goals and problems more accurately and plan resource management to control problems more efficiently than source control.

This report was submitted in partial fulfillment of Contract No. 68-03-2597 by the University of Illinois at Urbana-Champaign. The report covers the period September 1977 to August 1979.

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INTRODUCTION

This report compares two approaches to the agricultural nonpoint-source pollution-control problem: source control and instream water-quality management (ISWQM). This report will view controlling sediment as a stream water quality problem. However, it is recognized that there are other nonpoint pollutants such as pesticides and fertilizers. The authors feel that much of the discussion in this report will apply to non-sediment pollutants.* Source control is a strategy of controlling pollution loadings by using standards such as soil loss limits or best management practices (BMPs) without relating them directly to water quality goals. ISWQM is a strategy of determining water-quality goals by examining pollution effects and other considerations and developing a resource management plan for achieving those goals. ISWQM relates land management more closely to water quality goals. Source control focuses on a more manageable piece of the overall problem because the techniques to be used are relatively well understood and the institutional framework is in place to implement such an approach. Nevertheless, while the impacts of such a program on water quality may be significant and positive, the precise impacts are simply not well known, and the most effective source controls to improve water quality may be hard to specify. ISWQM, on the other hand, would capture a larger subset of problems, so the analytical problem would become much more difficult. In this report, we will discuss the strengths and weaknesses of each approach and suggest some intermediate alternatives that could be explored.

Institutionally, ISWQM requires a close integration of nonpoint-source pollution control with the management of water-uses and formulation of water-quality goals. A land-management plan defining BMPs or effluent standards would be related to water-quality goals for a stream and could be changed if the water-quality goals are not met. Under source control, the land-management plan is typically applied without analysis of the impacts on changes in water quality in a particular stream. The ISWQM planning process requires an institutional structure such that agencies defining water uses and managing water resources, agencies defining water-quality goals and standards, and agencies developing land-management plans must work together to relate land management to desired water quality. Under source controls, agencies planning land management could work independently of agencies defining water uses and managing waterways.

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* The authors are more familiar with sediment problems than other nonpoint pollution problems. J. B. Stall is a hydrologist who has made a career of studying sediment problems. All three authors participated on the Erosion-Sedimentation Subcommittee of the Illinois Task Force on Agricultural Nonpoint Sources of Pollution which advised the Illinois EPA in developing its statewide 208 plan.

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To be implemented effectively, ISWQM requires a feedback mechanism on water quality that, in turn, requires water quality monitoring and periodic reassessment of the effectiveness of pollution-control practices in achieving water quality standards. Periodic reassessment of plans is also needed to redefine goals and problems over time and to readjust plans in light of any new knowledge of pollution-control practices and land-use/water-quality relationships. Water-quality monitoring will also make possible advances in the state of knowledge of land-use/water-quality relationships. A source control approach would not involve this feedback mechanism.

There is also an intermediate approach between source control and ISWQM. An initial source control plan might be developed that simply applies technical standards. The performance of the plan is reassessed in light of water-quality goals and changed where performance is inadequate. This approach will be considered to be an ISWQM approach because land management plans and water-quality goals are being integrated in the planning process and a feedback mechanism exists to assess performance and change the plan. Oregon's 208 basin-assessment project appears to fit into this category (Rickert and Beach, 1978).

For convenience, two different cases of ISWQM will be considered. With the first approach, water quality goals or standards are precisely defined and a land management plan is developed to meet the water quality goals. The land management plan could then be "fine-tuned" over time to meet the water quality goals. With the second, simpler approach, priorities for pollutants would be defined based on their expected impacts on water uses. Critical sources of these pollutants would then be identified and land management modifications would be concentrated in these areas. The first approach would require a greater knowledge of the impacts of pollutants on water uses and the relationship between land management and water quality.

As will be discussed later in the report, it appears likely that difficulties in changing institutional structures, lack of information concerning land use and water quality, and the costs of planning and implementation will make ISWQM more costly and difficult to implement than source control. It seems likely that an ISWQM approach of precisely defining water quality goals for nonpoint pollutants and developing land management plans closely linked to those goals will only be used in special circumstances. (RCWP project areas could be such a circumstance.) Source control or the simpler ISWQM approach of identifying priorities for pollutants and critical areas of pollution sources for management would be used in other circumstances. For example, ISWQM might be applied to streams identified as having "critical" values such as esthetic or pristine characteristics to be preserved, special uses to be managed (e.g., navigation), or severe pollution problems. Source control could be applied to all other areas. Iowa has developed a procedure to identify high-value waterways with severe problems on which to concentrate management (National Association of Conservation Districts, 1978). Another approach would be to apply source control to achieve long-term productivity goals on all land and apply ISWQM later to address any remaining water-quality problems.

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A REVIEW OF AGRICULTURAL NONPOINT POLLUTION CONTROL POLICIES[1]

Two important laws define directions for agricultural nonpoint pollution control: PL92-500 and PL95-217. Section 208 of PL92-500 required the states to develop plans to control nonpoint sources of pollution. The governor of each state appointed agencies to develop statewide or areawide plans. EPA regulations required that a statewide policy advisory committee consisting of local elected officials, represenatatives of state and federal agencies, and representatives of the general public. The USDA, U.S. Army Corps of Engineers, and Department of Interior were to be invited to participate in area-wide policy groups. Public information and participation was required. The current EPA guidelines to 208 plans require that priorities be developed for pollutants and that critical source areas of those pollutants on which to concentrate control be identified. Hence, the EPA requires an ISWQM approach. It is not clear how closely these guidelines will have to be followed for a state's 208 plan to be acceptable. The plans must identify and evaluate measures needed to produce a desired level of control. The practices must be effective in reducing pollution problems. The plans must also identify agencies and programs to implement the plans. Existing agencies and programs should be used to the degree practicable with the establishment of new agencies to be avoided.

PL95-217 defines the Rural Clear Water Program (RCWP) which will provide a limited amount of technical and financial assistance to implement practices to control nonpoint pollution. Under the RCWP a number of demonstration areas or areas of special rural water quality problems will be chosen. The USDA and USEPA will choose project areas from lists supplied by the state governors. Technical and financial assistance will be given to landowners and farm operators to install practices which reduce water quality problems. At least 75% of the owners or operators in "critical" areas of pollution in a proposed project area must agree to participate if assistance is to be granted. The Soil Conservation Service will take a lead role in the RCWP through soil and water conservation districts (SWCDs), state soil and water conservation committees, or state water quality agencies. It must be emphasized that the RCWP does not supply funds for the entire nonpoint pollution program. Nor does it prohibit the states from using other state programs or funds to implement pollution control practices.

There appears to be a great deal of leeway in defining agencies and programs to implement 208 water quality plans. However, it seems likely that state agricultural departments, extension services, and soil and water conservation districts will be involved with 208 agencies in implementing water quality plans on agricultural lands in a great many states. Traditional soil and water conservation programs, with some modification, will

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[1] Information in this section was drawn from Groszyk, 1979, and Holmes,1979.

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probably play an important role in providing technical and financial assistance to agricultural landowners and farm operators who are implementing nonpoint pollution control practices. In addition, the RCWP, which is to provide technical and financial assistance for special project areas, will be implemented by the Soil Conservation Service. Hence, RCWP will reinforce the role of traditional agricultural agencies.

In summary, agencies are to be designated by the governor of each state to develop and update plans to control agricultural nonpoint sources of pollution on an areawide or statewide basis. A wide variety of agencies can serve as 208 agencies. Local government officials, state and federal agencies, and the general public are to be involved in the planning process. The plans are to define priorities for pollutants and sources of pollutants. Practices to improve water quality are to be identified in the plans. The plans are to designate agencies and programs to implement the plans. In addition, the RCWP defines a program of technical and financial assistance for applying practices in special project areas. It seems likely that traditional state agricultural and soil and water conservation agencies and soil and water conservation districts will play an important role in implementing 208 plans on agricultural land.

INSTITUTIONAL PROBLEMS AND CHANGES

A number of problems may result when SWCDs which have been traditionally concerned with agricultural productivity become involved in programs of implementing practices to improve water quality. Some changes in the way SWCDs have traditionally made decisions may result. Three problems could arise to create difficulties for SWCDs. First, some people may be excluded from decisions which they feel will affect their legitimate interests. Land management decisions made by a SWCD may affect the use of a waterway outside an SWCD. Also, in some states, only landowners can vote on decisions concerning the application of land use regulations even though nonlandowners may feel they have a legitimate interest in how land is managed to control water pollution. Second, decisions concerning land management, water use, and water quality might not be coordinated closely enough under current arrangements. In the past, for example, reservoirs have often been constructed without an erosion control plan to control siltation. The resulting loss of reservoir life could have been prevented by better coordination of land management and water use decisions. Third, SWCD decisions might not consider watershed level problems. For example, the land management decisions of one SWCD might result in high quality water entering a stream system. However, the land management decisions of a second SWCD might result in much lower quality water entering the stream system. Coordinating the decisions of the two SWCDs might result in a more efficient allocation of resources to reduce nonpoint pollution problems than allowing each SWCD to act autonomously.

Addressing the interests of people living outside an SWCD, the problems of coordinating land management and water use decisions, and watershed level problems indicates that coordination of local land management decisions at the state or regional level is needed. Developing 208 plans provides an

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opportunity to address these problems by bringing agencies and the general public together on an area or statewide basis to define water quality and land management plans to meet them. (Whether or not 208 plans will successfully address these problems is another question.)

SWCDs have traditionally had much discretion in determining which practices in a soil and water conservation program would be cost-shared and where they would be located. Under a source control approach (such as a program of meeting SCS t-values), a traditional program of providing the SWCDs with a list of practices and a source of funding and allowing them to operate autonomously might work reasonably well. Under ISWQM, more coordination of SWCDs' land management decisions would be needed to ensure that appropriate practices are applied to meet water quality goals. A 208 plan would provide some degree of coordination of SWCDs' decisions. However, a 208 agency might have to monitor SWCD decisions closely and indicate where changes in SWCD decisions should be made to pursue the plan. The criteria that SWCDs use to allocate funds and practices for purposes of agricultural productivity might not fit a 208 plan well. A greater degree of coordination would be needed when a land management plan is developed to meet a set of water quality standards than under a simpler approach of identifying critical source areas of high priority pollutants. The need for precision in locating practices may be less important in the second case. The greater the responsibility that 208 agencies are to have in coordinating the decisions of SWCDs, the more legal powers beyond the advisory role they should have. A proposal to give a 208 agency power over the actions of an SWCD would probably bring about political resistance from SWCDs. The greater the activity proposed for the 208 agency, the greater the resistance from SWCDs will probably be. Pollution control alternatives are listed in decreasing order of political resistance: 1) ISWQM - where a land management plan is developed to a set of precisely defined water quality standards, 2) the simpler ISWQM approach of identifying pollutant priorities and critical source areas, and 3) source control.

To give nonlandowners within an SWCD the right to vote on land use relations could require a change in many states' soil conservation district laws. Such a change could bring about strong political resistance from landowners.

The institutional changes suggested here are not believed to be radical. Coordinating agencies which restrict the powers of local governments have been implemented in many cases (Bosselman and Callies, 1971). Voting rights have changed. However, political resistance to these changes, particularly the movement away from local control, could make the implementation of an ISWQM approach difficult but not impossible.

DECISION MODELS AND INFORMATION CONSTRAINTS TO DECISION-MAKING UNDER SOURCE CONTROL AND ISWQM

An agency participating in the ISWQM process would ultimately be making recommendations for land management. The process should include evaluations of (1) potential demands for water uses, (2) the capabilities of a particular stream and others to supply different uses, (3) the opportunity costs of

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pollution-control strategies, and (4) the environmental and distributional impacts of alternative strategies. A management plan of the watershed's resources would be based on such an analysis and would consist of a set of appropriate uses for different sections of the watershed, water-quality standards, and land-management criteria. Models of the decision system would help planners to study the impacts of pollution-control alternatives. The purpose of this section is to discuss the limitations of available methods and information sources and how they would restrict the modeling effort and thus the planning process in the case of soil erosion and sedimentation.

Components of the Decision-System Model

The ideal decision system would consist of three components: (1) land management, (2) physical processes, and (3) water-use and water-quality criteria. The *land-management* component should model the production of goods, land management practices (including tillage and conservation practices) and crop rotations, and the opportunity costs of different land-management plans. The *physical* component should model the impacts of these land-management alternatives on runoff, sheet-and-rill and gulley erosion, the transport of sediment (and other pollutants) to streams, and the impacts on stream processes such as channel erosion and deposition. Ideally, the total amount of sediment moved, the suspended portion, and the variability of sediment loads over time at various locations in a stream, as well as other water-quality parameters, should be estimated.

The *water-use and water-quality criteria* component would (1) estimate potential demands for uses of a stream and the benefits of providing those uses (and, conversely, the damages caused by not providing them) and (2) include different relationships to estimate water-quality criteria for different uses. The analysis of alternatives would be conducted to determine the costs and benefits, the distribution of costs and benefits, and the environmental impacts of pollution-control alternatives.

Ultimately, the minimum desirable modeling arrangement for ISWQM would (1) relate land-management practices to the behavior of physical processes and, in turn, estimate water-quality parameters and (2) estimate the costs and benefits of the land-management practices. This type of model would provide decision-makers with an idea of the water-quality ramifications of different land-management plans. This information would be quite useful to those in the political arena.

Water-Use Goals

The process of defining appropriate uses for a stream is largely political and involves the balancing of interests. It can be carried out regardless of whether or not information sources to estimate uses of a stream are available. People can voice their opinions through the political process and present evidence concerning the uses of a stream.* Political influences

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*The Illinois EPA is currently experimenting with classifying streams according to uses and applying water-quality standards based on those uses.

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in the planning process can affect the determination of goals and their priorities, alternative courses of action to be considered, trade-offs between alternatives, and the alternative finally chosen. As a result, empirical analyses of demand and consumption are not necessary to determine appropriate uses. The USEPA requires as a minimum that all existing uses of a stream be protected (Iowa Law Review, 1977).

The role of empirical analysis of demand is to aid in estimating benefits generated under the alternative stream uses. This analysis would also be helpful in estimating values for stream uses considered in modeling efforts where costs of land management and values of stream uses were considered simultaneously. Both demand functions and cost accounting imply a weighting of preferences (i.e., interpersonal comparisons) based upon the distribution of wealth and legal and administrative structures that define rights and responsibilities in the market place (Samuels, 1972; Henderson and Quandt, 1958; Alchian and Allen, 1967). This weighing of preferences in the market might, in fact, be different from that generated through a political process. Resource allocations based upon demand or consumption analyses would be preferable to allocations based on the political process only if the weighting of preferences implied by these demand or consumption functions is "more desirable." The determination of the desired weights, however, would ultimately be resolved in the political process.

The problems of data availability and cost and the inability to specify units of measure for consumption and values of uses present significant barriers to the estimation of consumption and demand functions.* It will be cheaper and easier to estimate these functions if secondary data sources are available than if primary data must be collected, particularly if labor-intensive survey research techniques must be used. Although secondary data sources will generally be available to estimate water consumption by municipal and industrial uses, secondary data sources for water consumption by agricultural uses and for recreational uses often will not be available or will be of poor quality. Also, it will generally be difficult to measure consumption and values for most recreational uses. Because of these barriers and the costs of overcoming them, it may be necessary to limit the sophisticated analyses of demand or consumption to streams or lakes with particularly important problems or critical values that will justify intensive management efforts.**

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* Although there may also be problems with the validity of the methods of estimating these two types of functions, they will not be addressed here.

** The discussion of demand analyses will be limited to water consumption and recreational uses. However, uses such as navigation and commercial fishing could also be analyzed.

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Water Consumption

Water-consumption data from public or municipal water sources is readily available. Municipalities can be contacted to determine annual withdrawals and locations of withdrawals (Institute for Environmental Studies, 1977). The costs of treating municipal water are also available, thus providing a source of information to use in estimating the values or benefits of improving water quality (Jacobs and Timmons, 1974). Information on industrial withdrawals can be obtained through regional EPA offices by reviewing NPDES permits (Institute for Environmental Studies, 1977).

Estimating agricultural water consumption may be more difficult. Irrigation is generally the most important agricultural water use. Livestock watering and household uses could also be important. Cooperative Extension Service agents could be contacted to find out who irrigates, how much they irrigate, and what crops they grow. Numbers of livestock in a watershed could be a basis for estimates of livestock water consumption. Although this information can be obtained from the Census of Agriculture, it may be outdated. In states such as Illinois, annual estimates of livestock raised are maintained and could be used, but it would not be possible to determine whether the water was from surface-water or groundwater sources (Institute for Environmental Studies, 1977).

If estimates of consumption of water are needed that are more detailed or accurate than could be obtained from secondary data sources, data may have to be collected directly from farmers or from industrial managers. A variety of sources such as Cooperative Extension Service agents, chambers of commerce, and tax rolls could be used to define the populations to be sampled.

Demand for Recreation

Estimating demand for or participation in recreation activities will probably be more difficult than estimating water consumption. Three problems appear with recreation. It will be difficult to (1) define and sample user populations for some dispersed activities, (2) define some uses, and (3) develop measurement scales for some intangible values.*

Activities that are not site specific, such as hunting or fishing, will present problems because it will be difficult to identify participants. In general, survey research techniques of some form will be necessary since site-specific secondary data sources are generally not available. Unless there are a few locations by which people must pass, such as park entrances, it will be costly and time consuming to identify the users. In surveying users, it would be desirable to study how participation and willingness to pay would vary with success (e.g., fish caught) so that the value of clearer water can be established.

Defining uses can also present difficulties for estimating recreation

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*See Dwyer, Kelly, and Bowes (1977) for a discussion of techniques to estimate recreation demand.

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demand or participation. An important problem in defining uses would arise where seemingly closely related activities require significantly different qualities of water. For example, different species of fish require different water qualities. To the extent that fishermen prefer different species of fish, there are different user populations. In fact, there may be large contrasts among various types of fishing experiences and groups of fishermen.

Defining measurement scales for uses can also present difficulties for estimating recreation demand or participation. Measuring intangible values such as esthetics or solitude is extremely difficult. For example, it will be difficult to estimate the impacts of improving water quality on esthetic values and then estimating the economic benefits. As a result, it is difficult to estimate the demand for such values or the benefits of providing them.

The problem of obtaining site-specific or watershed-specific information suggests that an alternative approach be considered. Rather than attempting to make location-specific estimates of demand for uses, particularly recreational, it might be more practical to estimate demands for uses over a large geographic area using survey methods. Surveying such an area would be more practical than surveying a number of individual sites because the users of specific sites would not have to be defined as populations to be sampled. Priorities for uses could then be developed with political inputs from the interested public.

Once the priorities for uses and quantities desired have been developed, suitabilities of waterways for various uses would have to be evaluated. Each use would require a scale of suitability that would allow comparisons of the suitabilities of uses on all waterways. Criteria for suitability for a use could include the natural characteristics of the stream, its current characteristics, and the estimated costs of reducing pollution to meet the criteria for the use. It would be difficult, however, to develop scales or criteria for intangible values such as esthetics. Also, preferences for particular sites would be difficult to account for. With input from the public, an interdisciplinary team of scientists and resource managers could assess the suitabilities of the waterway for different uses.

The next problem would be to allocate appropriate uses to streams. One way would be to determine which waterways or portions of waterways meet the criteria for a use and then allocate to them the highest priority for that use. This allocation could meet some or all of the quantities demanded for compatible lower priority uses. This process would continue for each lower priority use in sequence of priority until the quantities demanded for each use were met or until all available waterways were allocated. In this way, demands for the highest priority uses would be met first and waterway uses that were incompatible with each other would be separated. One problem with this approach to allocation, however, is that it would neglect decreases in priorities for a use as the number of waterways allocated to that use increased. As a result, certain high-priority uses might be overallocated to waterways. The process described of determining priorities for uses, suitabilities for waterways, and allocation of uses is similar to the multipurpose planning process for the smallest units of the national forests

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(Thompson, Nygren, and Moore, 1976). A similar approach was used in developing the RARE II Draft Environmental Impact Statement (U.S. Forest Service, 1978).

In summary, the lack of secondary sources of data on consumption of or participation in water uses is not an important barrier to the determination of appropriate uses for a stream because goals for uses do not have to be quantified. People can voice their opinions and show evidence concerning the appropriate uses of a stream or watershed through the political process. The lack of secondary-data sources and other data problems, however, including difficulties of defining uses and user populations, could be costly barriers to any planning effort where there is an attempt to *quantify* goals for uses and trade-offs among uses. These barriers would also make it difficult to include a quantified water-use component in a model of the decision system. The amount of money that should be spent on collecting and analyzing such data should be determined by the importance of the problems being alleviated and the value of the attributes being protected. It seems likely that sophisticated data collection and analysis should be limited to those waterways with particularly important problems or critical attributes that will require intensive management efforts.

Water Quality Criteria

The definition of water-quality criteria is closely related to the definition of water uses because these criteria are statements of what water quality is needed for a certain use. Water quality standards (goals) could be based upon the criteria. Land management plans could then be developed to reduce the quantity of pollutants in the water to the standards.

Ultimately, water-quality standards would be determined along with water uses in the political process. Standards could be arbitrarily set to reduce the presence of undesirable or dangerous substances. It would be desirable, however, to base standards upon the biological and ecological impacts of those substances in order to improve stream quality and not to allocate resources to such reductions if they will not improve desired uses. Criteria for uses on which standards could be based have been developed that could be applied in the ISWQM process. Complete standards have not been developed, however, for a number of uses because the impacts of some substances are not well understood. This uncertainty is particularly a problem for developing standards for individual fish species or biological communities.

The approach of the Lake and Stream Classification Study (Institute for Environmental Studies, 1977) is to define a set of criteria for each broad classification of use (e.g., public water supplies, fish and wildlife propagation, recreation and esthetics, shellfish, livestock, irrigation, and different classes of industrial water use). The criteria are based on USEPA water-quality criteria and state standards. When appropriate uses are defined, the most restrictive criteria of the set defined for appropriate uses define the stream criteria.

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The lack of information to determine criteria for certain pollutants, and in some cases to identify substances as potential pollutants, makes it difficult to develop a complete set of criteria. The criteria for some substances, however, are well documented. For example, 0.3 mg/l of nitrogen and 0.01 mg/l of phosphorus are accepted by many limnologists as critical concentrations for nuisance blooms of algae (Mackenthun, 1969; Task Force on Agricultural Nonpoint Sources of Pollution, 1978). Also, water filters for farmstead water can filter out only so much sediment. Pressure sand filters can be used when turbidity does not exceed 20 JTUs (Jackson turbidity units), while in-line filters will not work when turbidity exceeds 5 to 50 JTUs (Oschwald, 1972).

The approach of defining criteria for broad categories of uses does not account for variations in water-quality needs within the category, particularly for fish and wildlife propagation. The Lake and Stream Classification Study, in its further research, has tried to define water quality and habitat needs for fish within the state of Illinois. Based on literature reviews and interviews of experts, Herricks has shown that there is a lack of published research concerning water quality and habitat needs for many species.* Research seems to be concentrated on a small number of game species, bass, and sunfish (Sparks, 1978). Many of the parameters developed for toxic chemicals and heavy metals are related to acute toxicities and are not related to the long-term impacts on the community or ecosystem (Sparks, 1978).

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In particular, the effects of different concentrations of sediment are poorly understood. Herricks used subjective judgments, based on the experience of Dr. Phillip Smith of the Illinois Natural History Survey, to estimate the tolerance of species to suspended solids. He also listed bottom conditions desired by species. Sparks (1978) documents a number of studies on the impacts of sedimentation on different species (Buck, 1956a; 1956b; Claffey, 1955, Gammon, 1970, Heinstra, Damkut and Benson, 1969; Vinyard and O'Brien, 1976; and Wallen, 1951). Bass and sunfish are the predominant species discussed. Sparks concludes that mean turbidity levels of less than 100 JTUs are needed to maintain desirable game species over time. Over this mean level of turbidity, "rough fish" will eventually dominate the ecosystem. With mean turbidity levels between 25 JTUs and 100 JTUs, however, the total production of fish decreases. Sediment on the bottom of a stream or lake is also important because habitat changes change species composition. Analyses are needed to determine the water-quality and habitat parameters for a large number of species and communities if water-quality standards are to be based on desired fish species. This type of analysis probably will be time-consuming and expensive.

Stall recommended that a sediment standard for streams in Illinois and other midwestern states be a geometric mean of 30 mg/l.** He feels this standard closely approximates 25 JTUs and is the effluent standard for

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*Personal correspondence with Edward Herricks, Professor of Civil Engineering, University of Illinois at Urbana-Champaign, 1978.

**Personal communication with John B. Stall, Consulting Research Hydrologist, 1601 S. Maple, Urbana, Illinois 61801.

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suspended solids from a point source in Illinois. Nevertheless, more work to determine a sediment-concentration standard is probably necessary.

One problem with defining a standard is that it often implies a critical value above which a certain use is impossible and below which the use is unimpaired. While it is conceivable that such a case may exist, there are commonly a broad range of concentrations over which a use could take place. The quality or extent of use often decreases as the pollution concentration increases. For example, Sparks (1978) points out that game fish are able to survive in a range of mean turbidity levels, but fish populations and rates of catch by fishermen might be greater at lower turbidity levels. In theory, one would set an optimal turbidity standard by comparing the benefits and costs of reducing turbidity to various levels.

Cairns (1968), writing specifically of sediment standards for fish species, argues that ultimately stream standards should be based on stream conditions rather than on arbitrary fixed standards. Variations in its ecological conditions need to be recognized in determining the water quality standards for each stream. Cairns argues that this process requires three stages in setting standards. First, a disregard of the ecosystem brings about damages. Hopefully we have left this stage behind. Second, arbitrary standards are applied within jurisdictions after the damage caused by no restraints is seen. Third, regional variations in ecology are recognized, resulting in more flexible standards. The time and costs required for research to obtain the necessary information may make the third stage difficult to attain.

There are good economic reasons for opposing uniform criteria. First, even under "pristine conditions," some of the standards could conceivably be exceeded in some streams. Second, resources allocated to reducing pollutants in order to meet water quality standards might be misallocated to reducing pollutants that do not limit the propagation of desired fish species or other desirable uses of the waterway.

Given that information is lacking with which to determine many water-quality criteria, it will be difficult to vary water quality criteria for individual streams by basing the criteria on the streams' ecology, as suggested by Cairns (1968). It would, however, be possible to modify "arbitrary standards" to specific uses and stream conditions by using professional judgments by experts such as ecologists to suggest variations in the criteria for different uses and streams would become subjective and, perhaps, prone to challenge. This process, however, could help to define the most appropriate pollutants to control in a watershed and, perhaps, reduce the cost of pollution control.

Physical Processes

The report will now focus upon the physical processes involved in sedimentation, an important component of nonpoint pollution. Models which have been developed to describe these processes will then be discussed. An

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examination of the strengths and weaknesses of the models for an ISWQM planning approach will be discussed.

Nature of Sediment

The sediment that is carried from midwestern corn-belt cropland downstream is predominantly fine-sized material. Figure 1 graphically relates grain sizes to various particle-size classes (American Geophysical Union and reported by the American Society of Civil Engineers, 1975). For 51 samples of sediment deposited in nine typical reservoirs in Illinois draining watersheds of 7.5 to 668 sq km (1.9 to 258 sq mi), the distribution of sediment grain size is as follows: sand, 1 percent; silt, 52 percent; clay, 45 percent; and organic matter, 2 percent. Thus, the sediment depositing in Illinois and presumably other midwestern reservoirs is predominantly clay and silt with almost no sand present. Eroded soil that enters streams and reservoirs tends to be more finely grained, on the average, than the surrounding surface soil (Swanson, Dedrick, and Weakly, 1969; Young and Mutchler, 1969), but, soil particles may move as aggregates (Foster and Meyer, 1972). These fine-sized materials are probably carried mostly as washload rather than bedload (the distinction between wash load and bed load is discussed in the section on streambed sediment transport) and thus are a function of the upland soil erosion. At any particular time the sediment load in the stream contributed as wash load is a function of the rainfall and runoff from the cropland.

Currently, most professionals still have doubt as to the effect of upland soil conservation in reducing downstream sediment yield. There is some evidence, however, that the traditional soil conservation practices do reduce sediment yield. These practices seem to reduce the silt and clay-sized sediment particles reaching the stream. These particles are transported as aggregates having an equivalent size to coarse silt particles. A study by Stall (1962) describes 17 documented cases of soil conservation effectiveness. The author located eight U.S. reservoirs that had been subjected to a detailed measurement of sediment. Considerable soil-conservation measures had been carried out on each of these watersheds. After a reasonable conservation program had been applied to each watershed, the reservoirs were resurveyed to document the reduction in the sedimentation rate. Of these eight reservoirs, a 28 percent reduction in reservoir sedimentation was shown in Lake Crook at Paris, Texas; and a 73 percent reduction was shown in City Reservoir No. 3 at Fairfield, Iowa.

The study by Stall (1962) also evaluated four watersheds in which suspended sediment was reduced. These four watersheds were all in the Tennessee Valley. In each case, forest cover had been increased, check dams built, vegetable cover increased, and improved pasture programs carried out. The suspended sediment and streamflow were measured at stream gaging stations. Reduction in suspended sediment over the years ranged from 33 percent at Parker Branch Watershed to 90 percent at Whitehollow Watershed. This study further describes the reduction in river turbidity that was accomplished by a reforestation program in Georgia. There tree planting, improved forest management, contour farming, grassing of waterways, and skid-trail stabilization efforts were carried over a period of years. During this same era, the

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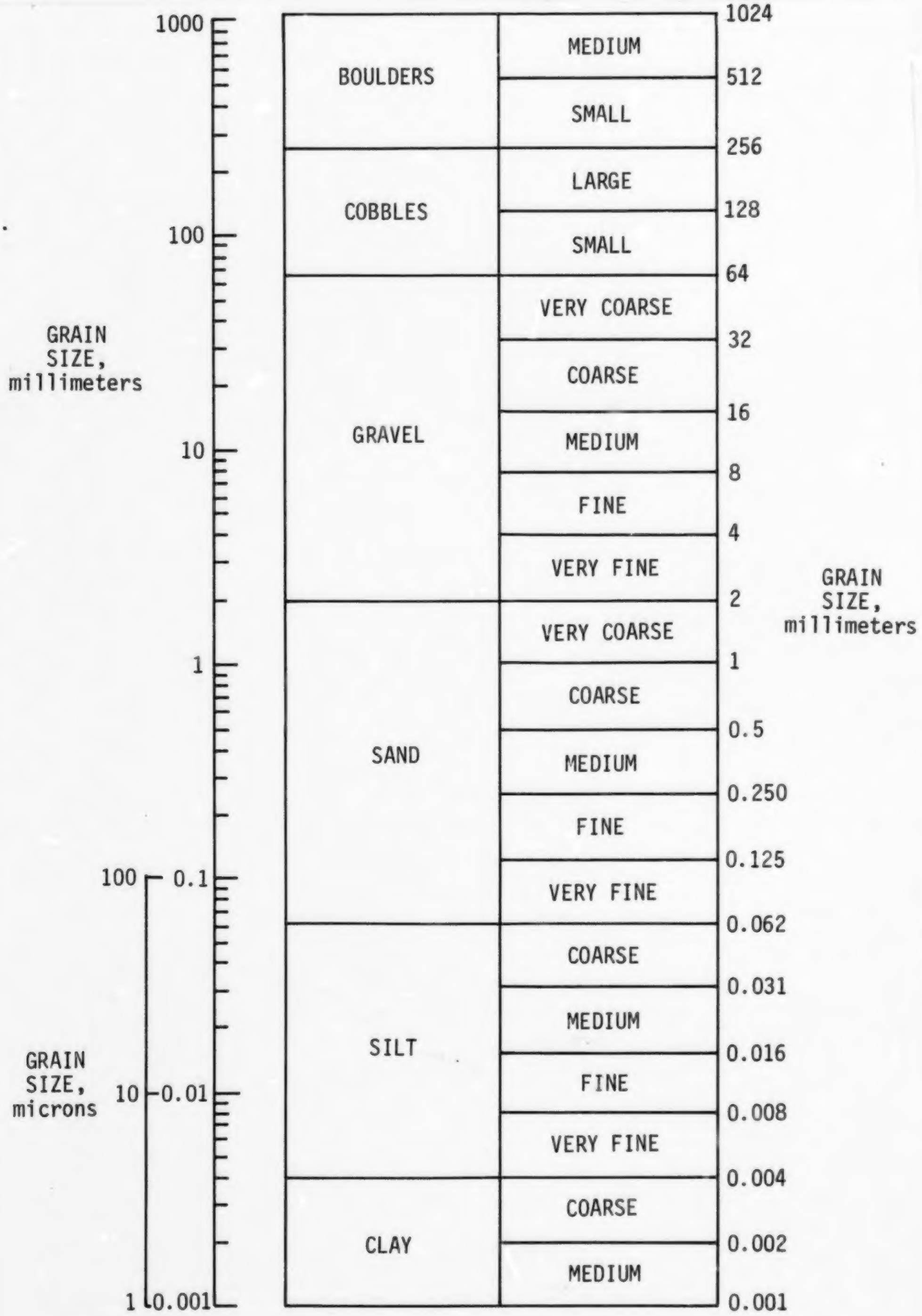
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SAND
SILT
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MEDIUM
SMALL
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VERY COARSE
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MEDIUM
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MEDIUM
1024
512
256
128
64
32
16
8
4
2
1
0.5
0.250
0.125
0.062
0.031
0.016
0.008
0.004
0.002
0.001
GRAIN SIZE, millimeters

Fig. 1. Names of Grain Sizes

turbidity of river water was documented at five different water treatment plants. At each of these plants the river turbidity was reduced. At Augusta, Georgia, on the Savanna River, turbidity was reduced by 44 percent; and at Macon, Georgia, on the Ocmulgee River, the river turbidity was reduced by 89 percent.

Although the results described are from only 17 selected cases, it does seem in each case that upland watershed conservation programs were effective in reducing the sediment yield downstream. Nevertheless, further documented studies are needed.

Runoff and sediment concentration vary over time. Storm events can result in overland flow of water which moves sediment overland and into streams. Between storm events, runoff and sediment concentrations will decrease. The Vermilion River at Pontiac, Illinois, draining 1500 sq km (579 sq mi) provides an example of how sediment and runoff vary over time in a typical midwestern watershed. The solid line in Figure 2 is the hydrograph of flow that occurred during August 1977. The dashed line in Figure 2 graphs the suspended sediment carried down the river by this storm. Shown in Figure 3 is a duration curve of suspended sediment in the Vermilion River at Pontiac for the year 1977. As can be seen, the annual geometric mean value is 102 mg/l. The median is 40 mg/l. For 60 percent of the days, or 219 days per year, the suspended sediment in this stream exceeded the level of 30 mg/l considered by some to be detrimental to fish. During the rest of the year, sediment concentration was below 30 mg/l.

Upland Erosion Processes

The universal soil loss equation (USLE), developed from measurements on nationwide experimental upland plots, calculates the upland soil loss that will leave the slope of the farmland if a free outfall exists at the downhill end of the slope. Under a condition of free outfall there are no obstructions to the flow of water or sediment. Usually the water runoff and the soil particles that leave the slope enter an almost flat swale, depressional area, strip of vegetation, or nonincised drainageway at the downhill end of the slope. Often most of the runoff water is held back from the nearest incised channel, or ditch, and the water infiltrates into the soil. The suspended soil particles are mostly deposited at the end of the slope in the same field from which they originated and are not delivered to the stream.

Several researchers have investigated the process of deposition at the end of a slope by examining sediment transport down a uniform slope and a concave slope with the same loss in elevation over the same distance. Neibling and Foster (1977) found that the amount of soil lost from a concave slope that they tested was 23 percent of the soil lost from a uniform slope. Young and Mutchler (1969) found that the sediment delivery from a concave slope was 38 percent of that on a uniform slope. The reason for the lower sediment delivery on the concave slope, of course, is that there was a large deposition of soil on the lower portions of the concave slope where the surface was becoming flatter.

A nonincised drainage way provides backwater onto the slope, creating a

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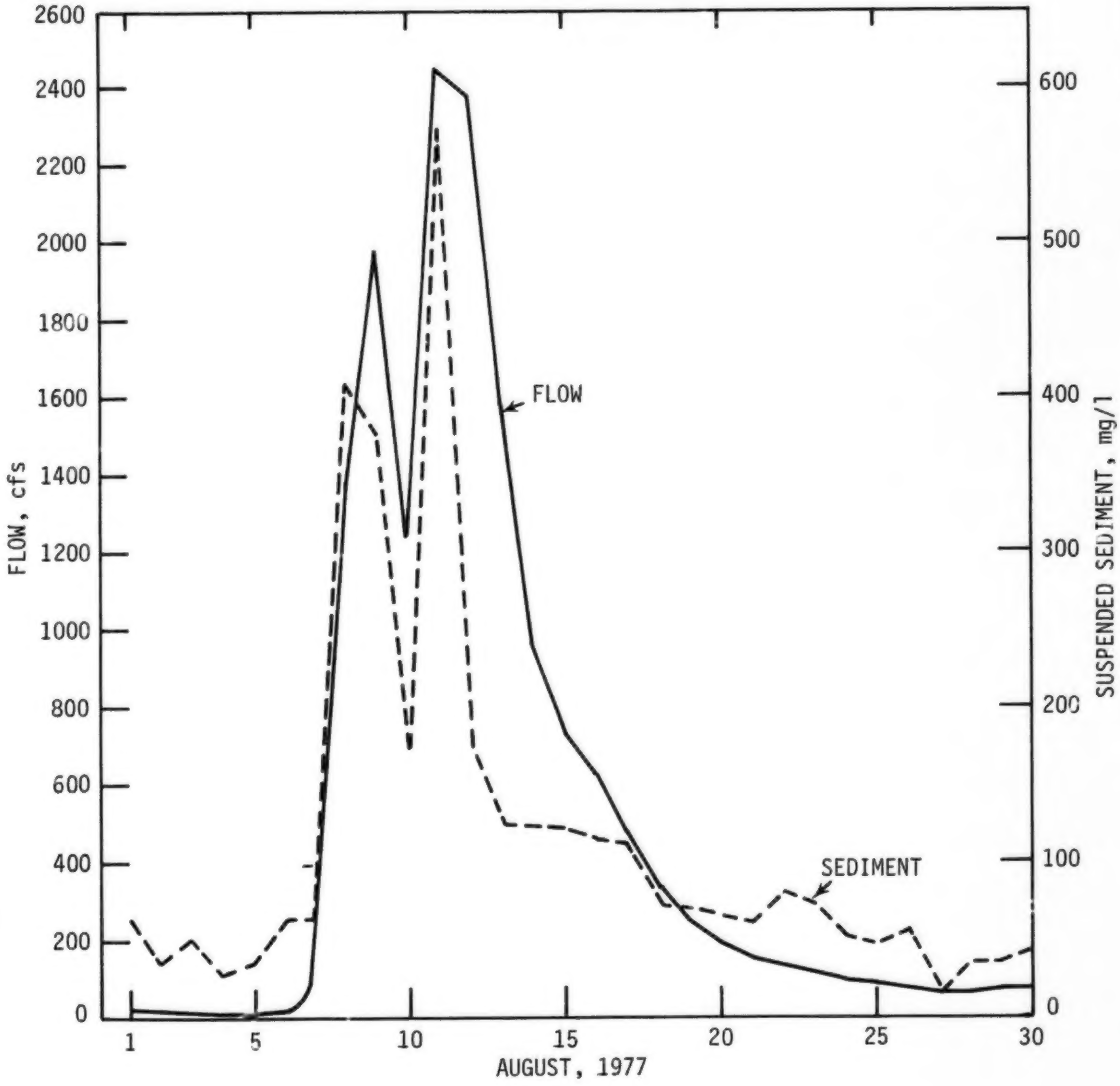

Fig. 2. Hydrographs of flow and suspended sediment for a storm during August, 1977, on the Vermilion River at Pontiac, Illinois.

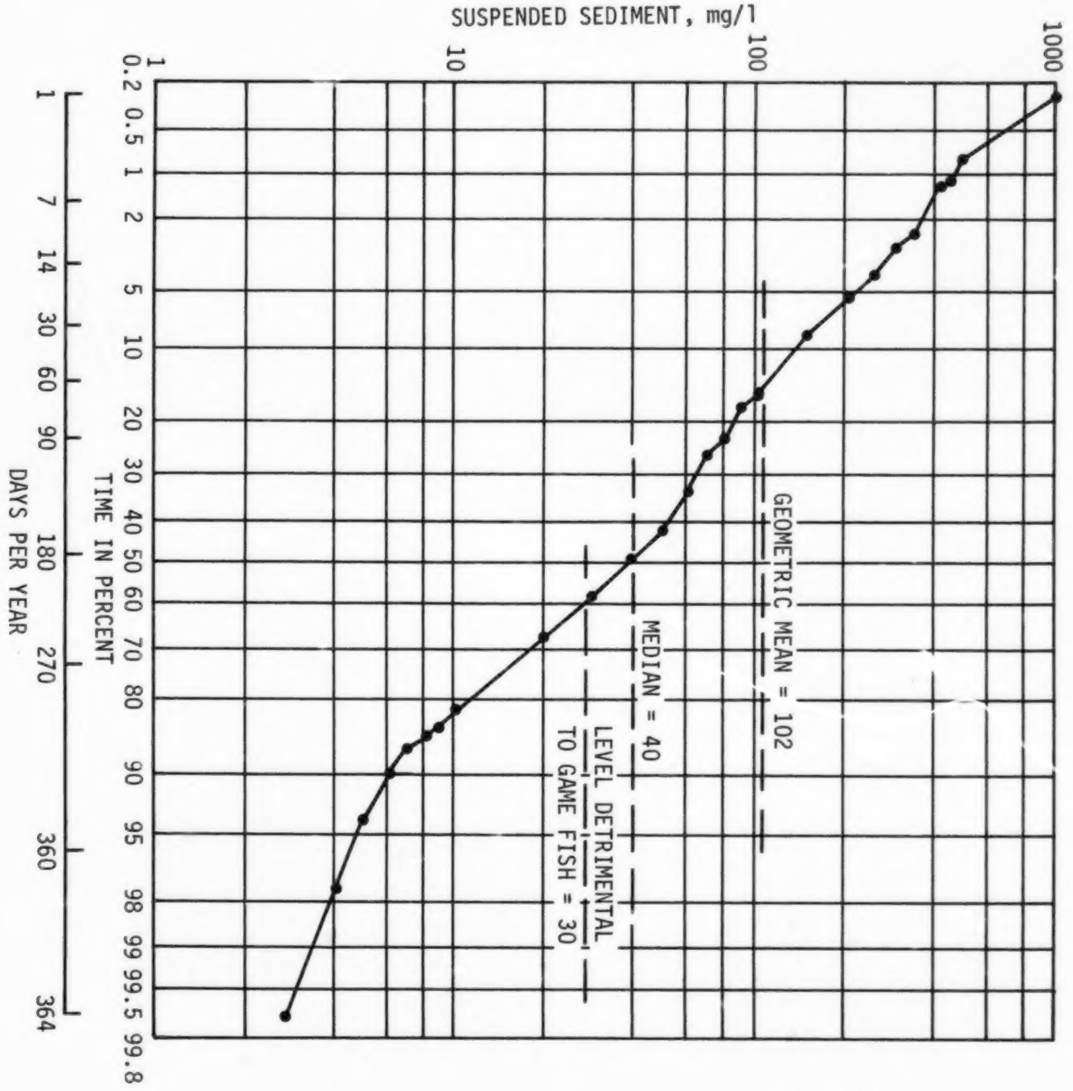

Fig. 3. Sediment duration curve for water year 1977 on Vermilion River at Pontiac, Illinois.

condition different from the free outfall at the experiment station plot. Nonincised drainage ways do not have distinct channels and can be crossed by a farm tractor and implement. Incised drainage ways are distinct channels of such size, shape, and magnitude that they cannot be crossed by a farm implement and tractor. Road ditches, natural ditches, or drainage ditches are incised drainage ways. If there is an incised drainage way at the downhill end of a cultivated slope, more of the upland soil is delivered to the stream than if there is a nonincised drainage way. Stall and Bartelli (1959) found that the quantity of sediment delivered to a reservoir decreased as the total length of nonincised channels in the watershed increased. The quantity of sediment trapped in the watershed system increased as the length of nonincised channels increased. Incised drainage ways trap very little sediment.

The presence of vegetated areas can also have an impact upon the quantity of sediment delivered to a stream. If runoff water leaving a cultivated slope and carrying soil particles is emptied onto a grassed area, such as a fencerow or pasture, soil particles will settle out in the grass. The flow of water will move across such a grassed area to reach a ditch. After a period of time, and if the water runoff is sufficient, the flow will cut a ditch or channel through the grass to create an incised channel or channels. When such channels form, they deliver more soil from the upland to the stream system, and downstream sediment delivery increases.

Tollner *et al.* (1976) simulated the effect of sediment trapped by grass strips. They predicted that the efficiency of a grass strip in trapping soil particles would vary with the size of the particles. The trap efficiency of grass strips varied from 80 to 100 percent for medium stand sand and from 1 to 5 percent for fine silt. For a more complete discussion of the impacts of vegetation on stream processes, see Karr and Schlosser (1977).

To better estimate sediment delivery from midwestern cropland, studies should be conducted to study runoff flows over typical soil types, with the zone between the farmed field and the nearest incised drainage way being the focus of research. Perhaps conditions in this overflow zone can be characterized to explain and predict the variations of sediment delivery which have been observed in Illinois to range from 10 to 50 percent of the upland soil loss.

Models of Sediment Processes

As a part of this study, a number of hydrologic and sediment models have been examined to determine their suitability for use in sediment studies. For a model of sediment movement to be valuable in the Midwest, it should be capable of showing how farming practices will affect the stream sediment. The model should also provide the temporal and spatial variability of the stream sediment concentration.

The models discussed in this section will be classified into two groups: planning models and research models. Planning models have been developed enough and are economical enough to be used for resource planning. Research models are developed for the purpose of furthering the state of knowledge of sedimentation processes. These concepts may be incorporated into planning

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models in the future. It is felt, however, that these models have not been adequately tested, are too expensive, or require too much data to be classified as planning models.

Sediment Delivery

Sediment delivery relates upland soil losses to the amount of sediment delivered to some downstream point. Sediment found in the stream is almost invariably a lesser amount than that calculated at the upland soil loss. The Task Force on Agricultural Nonpoint Sources of Pollution (1978) states that sediment delivery in Illinois streams varies from 10 to 50 percent of the upland soil loss. The American Society of Civil Engineers (1975) in their handbook *Sediment Engineering* provides a graph showing sediment delivery. This graph is based on a group of nationwide studies, and the same curve is provided by the U.S. Environmental Protection Agency (1975). This curve is derived primarily from data from Texas, Oklahoma, Nebraska, Mississippi, North Carolina, and Georgia. It is probable that in these regions the soil is predominantly sandy. If so, this curve is not particularly valid for the Midwest, except for areas where there are sandy soils.

A study in Illinois in 1977 compared the calculated upland soil loss from the 686 sq km watershed of Lake Springfield in central Illinois to the sediment deposited in the reservoir. It was found that the sediment delivery was 25 percent. If the value provided by the American Society of Civil Engineers (1975) were used, sediment delivery would be about 8 percent. Consequently, this example shows that sediment delivery in Illinois, and probably in the Corn Belt, varies widely from the curve and table presently used in the United States. In cases where the sediment is transported primarily as wash load, this sediment curve does not seem to be valid. Because a better understanding of sediment delivery is badly needed, further studies should be carried out to determine what factors govern sediment delivery.

Streambed Sediment Transport

Streambeds are carved by flowing water and are affected by the sediment carried by the stream. The streambed material is usually much larger than silt or clay and is usually comprised of sand, gravel, cobbles, or boulders. Einstein (1950) devised an equation to calculate the transport of bed material by a stream. He defined wash load as being that part of the sediment load that consists of grain sizes finer than those found in the bed. As can be seen in Figure 1, the gravel and cobbles are much larger than the clay and silt that comprise the wash load.

A stream system develops its hydraulics in accord with a pattern described by Strahler (1964). Hydraulic characteristics are related to the stream order. Stall and Yang (1970) showed that for 12 river basins in various parts of the United States, the hydraulic characteristics of the stream were related to the flow and to the drainage area. Drainage area was used as a substitute for stream order. The width, depth, cross-sectional area, and velocity of the stream were shown to increase in a downstream direction along the stream, following a consistent pattern termed *hydraulic* *geometry*. Yang and Stall (1974) showed that virtually all important physical stream processes are a function of the stream's unit stream power (USP), which is a measure of the rate of energy expenditure of the stream. Yang (1971a) showed that the tendency of the river to meander is governed by its USP. He also showed as a result of its USP (1971b) that the stream has a tendency to build riffles and pools along its bed. In addition, Yang and Stall (1974) showed that the sediment carried by the stream is best explained by the USP concept. For two natural rivers the USP has been shown to be superior to several other important suspended-sediment equations. Analysis of the sediment carried at 17 stream-gaging stations showed it to be dominated by the river's USP.

It was concluded by Stall and Yang (1970) that stream adjustments are made and governed by the USP concept. There is a hierarchy of levels through which the stream system can adjust itself to minimize the time rate of potential energy expenditure per unit weight of water, that is, the USP. This hierarchy is as follows:

First level--The stream increases bed roughness by building bed forms such as dunes and antidunes.

Second level--The stream creates bed undulations that depart from the uniform bed slope to form riffles and pools.

Third level--The stream attacks its banks to create meanders in the course of the stream.

Fourth level--The stream flow carves a longitudinal profile that has a slope in every reach adjusted to provide minimum stream power throughout the stream system.

The energy forces within the river dominate the construction and adjustment of the stream bed, including the transport of bed sediment by the stream as bed load or suspended load. These processes are virtually independent of the presence or absence of the wash load.

The movement of the wash load is thus superimposed on the movement of the bed material; the movement of the stream's wash load stops only when the stream flow stops. If upland soil losses are high, the amount of sediment delivered to the stream as wash load is high. If soil conservation measures are applied to cropland and soil losses delivered to the stream are reduced considerably, the wash load delivered to the stream is less. In both cases the stream will carry downstream virtually all of the sediment delivered to it. It seems that this reduction in washload will not have an important effect on the tendency of the stream to carry its bedload and to adjust its bed.

The clay and silt-sized particles carried as wash load may be deposited in pools in the stream during low flow periods. When high flows occur, these particles may be scoured out and again become wash load to be moved downstream. Game fish usually prefer to lay eggs in a sand or gravel stream bed. Clay or silt, carried by the stream as wash load and deposited in the stream bed, will cover the bed with mud, a much less desirable substrate or bed material because the fish eggs are not protected in the crevices as in the sand or gravel.The riffle reaches of the stream, however, will probably have a high enough flow velocity, even during low-flow periods, so that the stream bed will retain a sand, gravel, or cobble-sized bed material.

Planning Models

Stream Transport Equations

To understand movement of stream sediment throughout a basin, an evaluation is made here of sediment-transport equations. As described earlier, the concept of USP is a valid and dominant means for calculating and understanding the movement of sediment in streams. It is also possible to use the Einstein equation and modified Einstein equations, or several other approaches. These equations were all developed for sediment sizes much larger than the wash load in Illinois and midwestern streams. This fact indicates that streambed sediment is moved in a separate regime from upland soil loss or the movement of the fine sediment that is carried by streams as wash load. Since the detrimental impacts of bedload in the Midwest are considered relatively minor in relation to those of wash load, they could be neglected in land-use/water-quality models in that region without creating major errors.

Empirical Relations

A number of empirical models describing statistical correlations between upland factors and the amount of sediment produced have been devised for local regions. Empirical models providing physical input of the land factors often use some version of the USLE, or the same type data as used in the USLE, as input. When these factors are correlated with the downstream sediment yield, a statistical correlation factor or sediment-delivery rate is often incorporated as a statistical coefficient. Williams (1975a) writes such a relation as follows:

$$S = 95(Q\;qp)^{.56}\;K\;LS\;C\;P \qquad \text{(Eq. 1)}$$

where

S = sediment yield in tons
Q = volume of runoff in acre/feet
qp = peak flow rate in cubic feet per second
K = soil erodibility factor
LS = slope length and degree factors
P = erosion-control practice factor

This model was developed from 11 watersheds of about 7 hectares (3 acres), about five watersheds of 1.5 sq km (1.6 sq mi), and one watershed of 16 sq km (6.8 sq mi). These basins were located in Texas and Nebraska. This model has been evaluated and described by Mulkey and Falco (1977).

Empirical methods of relating sediment yield to watershed factors show some promise and seem to have value. The method described by Williams

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(1975b) is primarily a statistical correlation and does not simulate physical processes. The effects of upland farming practices on sediment yield cannot be defined objectively. The transferability of results from one place to another is not possible. The internal coefficients and exponents need to be determined by the statistical analysis of considerable observed data in any region in which they are used. The Williams (1975b) relation, for example, was developed for sandy soils in Texas and Oklahoma. While the relationship may be valid for areas with sandy soils, it probably would not be valid in the Midwest, where sediments are fine in size.

Williams (1978) describes a sediment-graph model based on an instantaneous-unit sediment graph as an addition to this sediment-yield model. The sediment is routed by a time-delay scheme described by Williams (1975a) to provide the travel time of sediment particles to a downstream location. The sediment-graph model was derived for agricultural watersheds in the Texas blackland prairies and may provide useful results for areas with similar soils.

LANDRUN

LANDRUN is a model developed at Marquette University in Milwaukee and described by Novotny and Chin (1976). LANDRUN has two submodels linked together to run sequentially. One predicts watershed runoff, and the other predicts watershed sediment yield. The LANDRUN model has been used by Sharpe and Berkowitz (1979), linked with a linear-programming model to evaluate the economics of farm management. The results provide a straightforward analysis of the Kewaskum-North watershed of 172 hectares (425 acres). LANDRUN calculates the hydrologic budget with Equation 2 as follows:

$$Q = P - 1 - DS \qquad \text{(Eq. 2)}$$

where

Q = runoff

P = rainfall

I = infiltration

DS = depression storage available

Infiltration is calculated using an equation devised by Holtan (1961). Seasonal values for the infiltration function are provided for various months of the year and for various crops.

LANDRUN generates sediment yield in a manner similar to the USLE but using the modified Equation 2 as follows:

$$SL = E\ LS\ K\ C\ P\ DR \qquad \text{(Eq. 3)}$$

where

SL = soil loss in tons per acre per simulation period (can be expressed in metric units)

E = rainfall runoff energy factor

where LS, K, C, and P are the same as for the Williams empirical method (Eq. 2) and Equation 1 and where DR - a delivery ratio factor. The rainfall runoff factor E addresses the fact that both rainfall and runoff can initiate erosion, and it is calculated with Equation 4 as follows:

$$E = RA + RU \qquad \text{(Eq.4)}$$

where

E = rainfall runoff energy factor
RA = rainfall energy factor
RU = runoff energy factor

The factor RA is the R factor taken directly from the USLE and is the kinetic energy of the storm multiplied by the maximum 30-minute intensity. The factor RU is the storm runoff volume multiplied by the peak runoff rate raised to the one-third power. The delivery ratio, DR shown in Equation 4, is made up of two delivery ratio factors calculated using Equation 5:

$$DR = DR_a \times DR_b \qquad \text{(Eq. 5)}$$

The first factor, DR_a, assumes that the amount of soil loss delivered is related to the fraction of rainfall that infiltrates as shown in Equation 6:

$$DR_a = 1 = \frac{I}{P} \qquad \text{(Eq. 6)}$$

where

DR_a = delivery-rate factor for rainfall
I = infiltration
P = rainfall

It can be seen that DR_a is essentially a percent runoff factor.

The second factor, DR_b, is also a sediment delivery and is the traditional sediment delivery ratio incorporated into the LANDRUN model. It is derived from observations from the watershed being modeled. For the Kawaskum-North basin, the delivery ratio, DR_b, of 10 percent yielded the best correspondence between the model and observed values.

The LANDRUN model uses predominantly physical relations. It has the one critical coefficient for sediment delivery DR_b, which is determined by local observations. The input needed for the LANDRUN model is virtually equivalent to that needed for the USLE. The example described by Sharpe and Berkowitz (1979) was for a basin of only 172 hectares. Its use on larger basins would probably be limited by the amount of input data required. The LANDRUN model has the advantage that the effect of upland farming practices on downstream sediment yield is based on physical predictable factors. This model appears to be rather good for sediment-yield studies.

ANSWERS

The ANSWERS model was developed by engineers at Purdue University for use in the Black Creek demonstration project in Indiana sponsored by the U.S. Environmental Protection Agency. The results of this project, including a description of the ANSWERS model, are provided by Lake (1977). The model is based on strongly supported physical relations, and it requires input similar to that needed for the USLE. Data from a contour map of the basin are also required. ANSWERS is a distributed model that provides a good representation of the spatial variability of land forms, land use, and hydrologic processes. It is also an event model, which means that it primarily

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models the results of one storm. It is possible, however, that the model could be used to estimate temporal variability of runoff and sediment by the use of a group of design storms that could be developed. ANSWERS is a deterministic model based on the idea that at every point within a basin there is a functional relation between the rate of surface runoff and the rainfall intensity, infiltration, topography, soil type, and other upstream factors. Further, these surface runoff rates can be used to model transport-related functions such as soil and chemical movement within the basin. The soil particles are detached by overland flow when the shear stress at the surface is sufficient to overcome the particles' gravitational and cohesive forces. Inter-rill erosion is described by equations published by Foster, Meyer, and Onstad (1977). The Holtan equation is used for infiltration.

In the ANSWERS model, the detachment of soil particles by raindrop impact is calculated using the relationship described by Meyer and Wischmeier (1969) and given as follows in Equation 7:

$$DR = .027\ C\ K\ A_i\ I^2 \qquad \text{(Eq. 7)}$$

where

DR = rainfall impact detachment rate, kg per min
C = cropping management factor, same as in USLE (Eq. 1)
K = soil erodibility factor, same as in USLE (Eq. 1)
A_i = area increment, sq meters
I = rainfall intensity, millimeters per minute

The detachment of soil particles by overland flow in the ANSWERS model is calculated as described by Meyer and Wischmeier (1969) and modified by Foster (1976), and given as follows in Equation 8:

$$DF = .018\ C\ K\ A_i\ S\ Q \qquad \text{(Eq. 8)}$$

where

DF = overland flow detachment rate, kg per min
S = slope steepness, or degree
Q = flow rate per unit width, sq meters per min

The ANSWERS model uses an expression for particle transport in overland flow that is based generally on a paper by Yalin (1963) and is given as follows in Equation 9:

$$T = 146\ S\sqrt{Q} \qquad \text{(Eq. 9)}$$

if Q is equal or less than .74 sq meters

$$\text{and } T = 14{,}600\ S\ Q^2 \qquad \text{(Eq. 10)}$$

If Q is greater than .74 sq meters

where

T = potential transport rate of sediment, in kg per min, per meter

In a final report on the Black Creek project by Lake (1977), the ANSWERS model was calibrated for a small basin of 714 hectares (1,765 acres or

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.75 sq mi). For one storm the rainfall was 64 millimeters. The calculated runoff was within 19 percent of the guaged amount, and the total sediment yield was within 13 percent of the observed amount. The report provided a runoff hydrograph and a sediment graph that seem valid and reasonable. The ANSWERS model also provided a map showing isolines of sediment loss for this 714 hectare basin. The ANSWERS model was thus used to evaluate the effects of contouring and minimum tillage on selected regions within this basin. It was illustrated that by controlling erosion on just two small parts of this basin the downstream sediment yield was reduced significantly.

The example provided in the Black Creek project was for a relatively small basin of only 714 hectares. The present program, however, can handle a maximum of 2,000 watershed elements, which means that it could be applied to a basin of about 81 sq km (31.2 sq mi).

ARM

The ARM model is the agricultural runoff management model. It has been devised by the Hydrocomp Inc. company under the sponsorship of the U.S. Environmental Protection Agency. This model has been described in important publications by Donigian and Crawford (1976) and by Donigian *et al.* (1977). The ARM model contains soil-loss functions that are different from most others but that appear to be valid. It is based on the continuous simulation of flow originally conceived as the Stanford watershed model and later developed by the Hydrocomp Company as their hydrologic simulation programming, HSP. The HSP has been used widely throughout the United States in solving many hydrologic problems. Accompanying the basic hydrologic model are models of pesticide absorption-desorption, pesticide degradation, and nutrient transformations. In the ARM model, only the sheet-and-rill erosion is included. The detachment of soil fines and silt and clay fractions (by raindrop impact) and the transport of soil fines by overland flow are calculated.

In the ARM model *detachment* of soil fines is calculated using Equation 11 as follows:

$$RER(t) = (1 - COVER(T)) * SMPF * KRER * PR(t)^{JRER} \qquad \text{(Eq. 11)}$$

where

$RER(t)$ = soil fines detached during time interval t, in tons per acre
$COVER(T)$ = fraction of vegetal cover as a function of time, T, within the growing season
$SMPF$ = crop-management factor, same as P in the USLE (Eq. 1)
$KRER$ = detachment coefficient for soil properties
$PR(t)$ = rainfall during the time interval, inches
$JRER$ = exponent for soil detachment
$*$ = multiplication

In the ARM model the *transport* of soil fines is calculated using Equation 12:

$$SER(t) = KSER * OVQ(t)^{JSER}$$

if SER(t) is equal or less than SRER(t)

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$$= SRER(t) \qquad \text{if } SER(t) \text{ is greater than } SRER(t) \qquad \text{(Eq. 12)}$$

where

SER(t) = transport of fines by overland flow, tons per acre
KSER = coefficient of transport
OVQ(t) = overland flow occurring during the time interval t, in inches
JSER = reservoir of soil fines at the beginning of time interval t, in tons per acre

In the operation of the model the soil fines detachment RER during each 15 minute time interval is calculated by using Equation 11 and added to the total fines storage SRER. Next, the total transport capacity of the overland flow, SER, is determined using Equation 12. Sediment is assumed to be transported at capacity if sufficient fines are available. Otherwise the amount of fines in transport is limited by the fines storage SRER. The sediment loss to the waterway in a time interval is calculated using the fraction of overland flow that reaches the stream, as in Equation 13:

$$ERSN(t) = SER(t) * F \qquad \text{(Eq. 13)}$$

where

ERSN(t) = sediment loss to the stream during the time interval t, in tons per acre
F = fraction of overland flow reaching the stream during the time interval t

Land covered by growing crops and crop residue has an impact on sediment loss. It is allowed for in the ARM model using the land-cover variable in Equation 11 denoted as COVER(T), which represents the fraction of the land surface effectively protected from the kinetic energy and detachment capability of rainfall. Monthly values of this cover are specified. Judicious use of the land-cover function allows the simulation of various land-surface conditions for different practices. The effect of tillage operations is to increase the mass of soil fines available for transport.

As reported by Donigian *et al.* (1977), ARM can represent runoff, sediment, pesticide, and nutrient loads from small agricultural watersheds in Georgia and Michigan. The calculated sediment and nutrient levels have agreed fairly well with the observed levels. The model shows that the loss of nitrates and soluble pesticides is highly related to the simulated *interflow* component of water runoff. That is, a change in the amount of surface runoff and an increase in the amount of water infiltrating into the earth provides a change in the nitrate and pesticide constituent. It is reported by Donigian *et al.* (1977) that watersheds greater than 2 to 5 sq km (0.8 to 1.9 sq mi) are approaching the upper limit of applicability of the ARM model. Because this model provides for continuous simulation of flow, sediment, nitrogen, phosphorus, and such things as oxygen, it is probably the best of those evaluated for the purpose of depicting sediment and water quality. It reveals secondary effects like the change that conservation practices will bring about in subsurface flow and the resulting change in the nutrient budget.

The input data needed to operate the ARM model are considerable. It

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requires relatively large computer storage and large amounts of computer time. In addition, the maximum basin size of 5 sq km is probably a limiting factor. These problems mean that the ARM model will probably not be adopted for basinwide water-quality planning.

The 1979 SEA-AR Sediment Planning Model

The U.S. Environmental Protection Agency (1975; 1976) published Volume 1 and Volume 2 of the report *Control of Water Pollution from Cropland.* Volume 1 was a handbook and Volume 2 was an overview of how sediment moves from cropland into streams and how pollutants similarly move. These two volumes summarized the available information on this topic from the Agricultural Research Service (ARS) of the U.S. Department of Agriculture. In 1978, the agency was renamed the Science and Education Administration--Agricultural Research, SEA-AR.

During 1978 the SEA-AR took a new initiative to provide a new field-scale sediment planning model. The immediate purpose of this effort is to estimate the movement of pollutants from agricultural lands to streams and to assess the effectiveness of current and future land-use practices on this movement. The scope of this effort has been to compile a state-of-the-art combination of known results from agricultural experiment stations in the United States to make a readily usable system, on a field-size scale, to quantify the effects of best management practices (BMPs) to reduce pollutant movement.

This SEA-AR sediment model is to be applicable at the field size, that is, perhaps 20 to 40 acres. The input to the model is to be simple, straightforward information of the type readily available. The model is conceived to be a compilation of unit practices and information that would have some similarity to the USLE. The model is to characterize the results of existing agricultural physical conditions on croplands and existing cropland practices to predict soil loss and sediment movement as well as the movement of pollutants off of a field. The model is to contain: a group of hydrology functions, a group of erosion and sedimentation functions, and a set of chemistry functions. The operation of all of these functions is to provide an understanding of the movement of sediment and pollutants from the field slopes into the streams leaving a field-sized areas. A working group of 50 to 75 research scientists of the SEA-AR have been assigned to provide the model functions within these three principal areas of the model.

The input needed for the hydrology model is either daily or hourly rainfall. Its output will divide the rainfall into two categories daily: runoff and infiltration into the earth.

The chemistry model will require an input as to the nutrients in the watershed soil. It will utilize the results of the hydrology-and-erosion model and will provide estimates of the nutrients that leave the field in the water runoff, that leave the field with or attached to the sediment, and that leach through the soil to the groundwater. The chemistry model will also provide for the nutrients utilized in plant growth, which amount is subtracted from the nutrients available for leaching into the groundwater. This

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model will require input as to the properties of various pesticides as to whether they are normally transported in solution or attached to sediment. Also to be provided is an enrichment ratio for pesticide-transported pesticides that are preferentially transported by clay and organic matter.

The erosion-sediment functions in this model will be based on the physical laws governing the detachment, transport, and deposition of soil particles as these factors occur on the watershed field. The required information will largely be those factors required to solve the USLE. In addition to that information, data will be required on the primary size distribution and the specific gravity of the particles eroded from the soil. It is felt that this type of information can readily be obtained. The sediment-yield model will provide the amount and concentration of sediment moved from each element of the field during each storm. It will also provide the total sediment yield.

Because the erosion-sedimentation model is based on the physical laws governing the detachment, transport, and deposition of sediment particles, it will not be required to estimate what is usually called *sediment delivery*. The detachment, transport, and deposition functions are calculated for elements of the field-size watershed based on existing farming practices. It is also readily possible to calculate the same detachment, transport, and deposition amounts of the sediment as a result of particular soil conservation measures. This factor will make this model useful in evaluating upland soil conservation.

The SEA-AR sediment planning model will be useful to generate peak amounts of flow, sediment, pesticides, and nutrients and to evaluate acute pollution problems. It will also simulate the general daily runoff and percolation losses to use in the evaluation of chronic pollution problems.

The selected research personnel within the SEA-AR have been focused during the past year on the development of this state-of-the-art sediment planning model. In addition, the group is to approach the development of a sediment planning model for a watershed or basin-size area that would model areas much larger than the 1979 field-scale model.

The State of Sediment Research Modeling

Neibling and Foster (1977)

Neibling and Foster (1977) describe sediment yield from overland flow processes. This study derives and provides considerable theoretical support for equations to represent the physical processes involved in sediment detachment, transport, and routing. The authors report that eroded soil particles and that most overland flow of aggregates and sand upon entering the stream is transported as bed load. As a result, they use the Yalin sediment transport equation and calibrate it for the agricultural field conditions. They develop a soil-erodibility graph similar to the one described by Wischmeier, Johnson and Cross (1971). This nomograph was developed for 40 different bare Indiana soils.

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The authors develop an equation to provide the basic relationship between transport capacity, runoff flow energy, and slope length and steepness. The sediment routing algorithm described by Meyer and Wischmeier (1969) is utilized. An example analysis is made for bare soils of a uniform slope and a composite slope showing the sediment availability, transport, and deposition for various parts of the slope.

Li, Simons, and Shiao (1977)

Li, Simons, and Shiao (1977) describe and provide an elaborate research mathematical model describing the entire soil detachment and transport process. A silvicultural application of this model is discussed in Li, Eggert, and Simons (1979). In this model, the interception and infiltration losses are subtracted from the actual rainfall. The remaining water becomes runoff. The runoff wave is calculated using a kinematic wave model that makes the model costly to use. This process has been described elsewhere by Li, Simons, and Stevens (1975). This routing procedure is used to compute overland flow and channel flow. The overland flow computations include the effects of rainfall on the flow resistance. For shallow flow the impact of raindrops causes energy loss in the flow in addition to that caused by the rigid boundary of the channel. The validity of this routing procedure has been calibrated and confirmed on a small paved parking lot at Johns-Hopkins University in Baltimore.

The Li, Simons, and Shiao (1977) sediment model calculates the sediment supply as that caused by soil detachment by raindrop impact and surface runoff. The sediment load is broken into two main categories (bed material and wash load) and into a specific number of size fractions. The transporting rate for each sediment size is divided into the bed load transport rate and the suspended-load transport rate. The Meyer-Peter bed load transport equation is used although the authors state that any suitable bed load transport equation might be used. The suspended load is calculated as a function of the sediment concentration at any point above the bed.

The soil-detachment function includes an accommodation of surface changes on the soil as a result of armoring. The sediment size D_{84}* is used to estimate the thickness of the armored layer.

This sediment model is generally calibrated on a bare area of mine spoil in Colorado about which considerable data are available on particle size, slope length, and degree as well as the size distribution of the eroded material. The calculated and simulated hydrographs and sediment graphs reasonably compare.

This model is a valuable research tool. The understanding developed with it will undoubtedly be of value in future sediment studies.

Simons et al. (1977)

Simons *et al.* (1977) describe a simple procedure for estimating soil

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* 84% of the sediment particles will have a larger diameter than D_{84}.

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erosion. For this model the interception, infiltration, runoff routing, and sediment transport capacity are largely similar to the above-described model of Li, Simons, and Shiao (1977). This procedure is more simplified, however, in that, instead of routing all of the sediment load as a large number of particle-size fractions, the single representative particle size D_{50} is utilized. The authors show that the simplification of the model provides reasonable general results. The Li, Simons and Shiao (1977) model requires computer time 10 to 15 times greater than this model by Simons, *et al.* Savings in computer time are enormous, and the results are more simplified and limited.

Smith (1976)

Smith (1976) describes a distributed watershed erosion and sedimentation model. In the initial step in this model, the incoming rainfall is divided into the infiltration and runoff. The point-rainfall detachment rate is calculated, as is the detachment rate of sediment by the hydraulics of the flow. The model employs the USP relation described by Yang and Stall (1974) as a sediment transport function. The other inputs are generally the physical inputs required by the USLE.

This model is an experimental research one calibrated for storms on a small watershed in Arizona. Although it is not a readily available engineering planning tool, its results are promising. It provides a time-distributed output of runoff and sediment from a small upland watershed.

Onstad, Piest, and Saxton (1976)

Onstad, Piest and Saxton (1976) provide a sophisticated research model. Soil detachment is described as the detachment by rainfall energy and by flowing water. The transport capacity depends on the slope degree, length, and physical factors. The input to this research model is largely that required for the USLE.

This model was calibrated for research watersheds near Treynor in southwest Iowa. On one watershed, 62 rainfall events were evaluated, and on the other watershed 48 rainfall events were evaluated. The model predicts sediment yields from single storms. The individual storms tested produced sediment yields of 0.01 to nearly 50 tons per acre, and the model predicted storm sediment quite accurately.

Woolhiser and Renard (1978)

It is possible to calculate the sediment yield at any point along a stream system as a complex residual of many stochastic processes. In the paper, "Stochastic Aspects of Watershed Sediment Yield," Woolhiser and Renard (1978) have given a description of several stochastic models. Many components of the sediment-yield processes are best described by their probabilistic structure because randomness is the very essence of the individual processes. The most obvious source of randomness in sediment yield from upland areas is rainfall. Other sources include factors such as the raindrop size, wind effects, soil-infiltration rates, and erodibility. Sediment-yield

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models based on stochastics range from detailed physically-based models with distribution functions obtained by sampling from Montecarlo simulations to empirical, event-based models for which distribution functions of sediment yield are obtained analytically.

Conclusions Concerning Physical Processes

Findings

It appears now that there is no one model available for planning the control of agricultural nonpoint-source pollution on a basin approaching the 13,000 sq km (5,000 sq mi) of one of the examples cited, the Sangamon River Basin. Because the LANDRUN, ANSWERS, and ARM models all seem to simulate physical processes, it would seem best to use one of these models for various representative areas within a total basin and then generalize the results using judgment based on watershed characteristics. As reported here, the LANDRUN model was effective when used on a 1.7 sq km (0.65 sq mi) area. The ANSWERS model has been used on an area up to 81 sq km (31 sq mi), and the ARM model has a maximum size limit of approximately 5 sq km (1.9 sq mi). All three of these models seem to accurately reflect the physical processes, the ARM model being the most sophisticated, the ANSWERS model being distributed and an event model, and the LANDRUN model being a lumped model that can be used to provide monthly or annual sediment yields.

Effect of Basin Size

In 1979 there is no existing sediment modeling procedure that can accommodate the sediment problems of an area the size of the United States, of the Water Resource Regions, or of the principal river basins. For these types of sediment problems, the sediment loads of the waterways are estimated from water samples. Various sources of sediment such as upland erosion or streambank erosion are then studied to estimate their contribution to the total problem. Sediment sources causing severe problems can be pointed out in this way. A study of this kind has been carried out in the eastern half of the United States by the Soil Conservation Service (1977). This method has also been used on a number of large river basins such as the lower Colorado (Johns, 1976) and the upper Colorado (Workman and Keith, 1975), on the Eel and Mad Rivers in California (California Department of Natural Resources, 1970), and on the upper Mississippi (U.S. Army Corps of Engineers, 1970). The method also had to be applied to small subbasins of the upper Mississippi of 259 sq km (100 sq mi).

Existing sediment models, however, could be used for sediment movement out of small watersheds within a larger basin. To provide a meaningful understanding of the sediment movement at downstream locations within the basin by generalizing such results, more must be known about sediment delivery in amount and time. The amount of sediment delivery is now predicted by methods that are generally valid for sand-sized sediment. For the silt-and-clay-sized sediment of the midwest Corn Belt, no existing method to predict a delivery ratio without an empirical measurement is valid.

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To estimate the time of delivery of the sediment from a small watershed to a downstream location, it is necessary to perform a hydraulic routing of the sediment from the upstream watershed to the downstream location. This routing can probably be accomplished largely by a procedure that merely provides the time delay required for the sediment-laden water from the upstream watershed to flow down to the downstream location. Williams (1978) has described a simple time-delay routing procedure for translating a sediment graph from an upstream to a downstream location. This procedure would be needed if there were a concern about sediment duration curves for such purposes as estimating impacts on fish. Further research is needed to provide better understanding of sediment routing. It also appears difficult to model the deposition of wash load in pools in the stream.

Time Variability

To understand sediment movement, it is necessary to know the time distribution of the sediment load of a stream. This information is particularly important for studying impacts on fish. When and how often does the sediment move? This time sampling is provided in different ways.

In the ARM model, an actual record of hourly rainfall for a long time period of perhaps 20 years is used. This rainfall is input to the model, and hourly or daily output is simulated for the basin modeled. This simulation is continuous and gives the best possible time sampling because it models all the events that have occurred and provides the predicted water runoff and sediment runoff.

These results can be plotted for a particular event to show the hydrograph and sediment graph for that event. These graphs would look similar to the ones in Figure 2. These same results from the ARM model can be analyzed to provide a suspended-sediment duration curve similar to that shown in Figure 3. Using ARM, the upland farming practices could be altered to reduce soil losses, and the entire 20 years could be resimulated. Those results could be analyzed to give a different, lower suspended-sediment duration curve. The reduction in the days per year that suspended sediment concentrations were predicted to exceed a particular level, as in Figure 3, could be compared with the costs of the upland farming practices that caused the reduction.

The LANDRUN model does not provide a hydrograph, a sediment graph, or a suspended-sediment duration curve. As a result, it is not particularly useful for studying the impacts of changing land-use patterns on fish habitat. It provides only the soil loss from a watershed in tons per hectare per year. As used by Sharpe and Berkowitz (1979), however, some time sampling was provided. They developed a 20-year record of the rainfall energy factor R showing its value each year. These values were ranked and assigned probabilities within the 20-year period. The LANDRUN model was run using the R factor expected at recurrence intervals of about 20, 10, 5, and 2 years. The annual soil loss for the watershed for each recurrence interval was calculated.

A graph of annual soil loss versus return period was presented that is a time sampling. Upland farming practices were assumed, and different sets of

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soil losses were calculated and plotted. The benefits of the reduced soil losses could thus be compared with the costs of the farming practices.

The ANSWERS model is an event model that provides a hydrograph of runoff and suspended sediment for an actual or a design storm. It does not provide a duration curve of flow or suspended sediment. To develop a suspended-sediment duration curve, one would have to develop a set of design storms and assign them recurrence intervals, which could best be done by analyzing a recorded rainfall record for a period of 20 years or more to get the occurrence and timing for each year of the rainfall events to provide the amount of the rainfall energy factor R. This analysis would be similar to the one made by Sharpe and Berkowitz (1979), which provided time sampling for the LANDRUN model. Such a record of R throughout each year of the 20-year period could be used with the ANSWERS model to provide the time sampling.

Traits of Models

Below are summary statements about the advantages and disadvantages of some of the models and methods studied here.

An advantage of all the models is that their physical input is similar to the input factors of the USLE. Thus these factors can be readily altered by assuming that upland farming practices are changed. This change in farming practices is then reflected through every model to show the effect on sediment yield.

A disadvantage of all the models is that they are all currently limited to very small watersheds and provide the sediment yield at the outflow of small hydrologic units only. Moreover, no model provides any physical basis for modeling the routing of sediment delivered from the outlet of this small basin to a point downstream.

The timing of sediment delivery from an upstream basin to a downstream point is not now provided in any model reviewed here except the Williams empirical model. It could probably be provided, however, by a simple time-delay sediment routing. The temporary deposition of wash load in stream pools is not accounted for, and no methods appear to be available for modeling.

Summary of Advantages and Disadvantages of Planning Models

ARM

Advantages:

Well based physically
Has sophisticated hydrology
Simulates all components of hydrology
Models nutrients and conservative pollutants
Time series output
Is being tested on a number of data sets not used in developing the model

Disadvantages:

Has maximum size basin of 5 sq km
Requires as input hourly rainfall data on the basin for a long time period
Uses large amounts of computer time and is thus relatively costly
Is a lumped parameter model

ANSWERS

Advantages:

Is well based physically
Is a distributed model; solves the many parts of the basin
Models flow and suspended sediment
Currently has a maximum size basin of about 81 sq km
Requires moderate computer time and cost
Can provide results for various sized sediments
Has been tested on data sets not used in developing the model

Disadvantages:

Is an event model
Needs a 20-year record of rainfall factor R to provide time sampling
Requires considerable land input data
Considers only sediment and not other pollutants at this point in time

LANDRUN

Advantages:

Is well based physically
Needs simple input
Provides annual soil loss in tons per hectare per year
Requires moderate computer time and cost

Disadvantages:

Is a lumped model; solves the basin as one unit
Needs a 20-year record of rainfall factor R to provide time sampling
Has been demonstrated on only a 1.7 sq km basin
Considers only sediment
Does not provide results for various-sized sediments

Empirical Methods

Advantages:

Need simple input
Require moderate computer time and cost
Have already been developed for Texas-Oklahoma sandy soils

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Disadvantages:

- Are statistically based; not physically
- Have not proven valid for silt and clay soils of the Midwest
- Provide no time sampling
- Often consider only sediment
- Valid only for the data set used to develop the model (Do not provide results for various-sized sediment.)

SEA-AR

Advantages:

- Is well based physically
- Has sophisticated hydrology
- Provides continuous simulation
- Models nutrients and pesticides
- Requires simple information to predict erosion
- Can provide results for various-sized sediments
- Has been tested in data sets not used in developing the model

Disadvantages:

- Has current field-size model of 20 to 40 acres
- Requires hourly rainfall data
- Is a lumped parameter model

Needed Research for the Land-Use Water-Quality Linkage

A number of recommendations for future research will be made in light of the examination of strengths and weaknesses of the various models.

Damage to Water Quality

1. Studies should be made of water pollutants such as fertilizers and pesticides to determine the extent to which they are carried into water while attached to sediment particles.

2. Studies should be instituted to model the ecologic stream environment to define the role of the streambed material and the sediment carried by the stream in the total use of the stream environment by aquatic life. For example, a typical stream reach in the humid part of the United States could be studied. The typical food chain, aquatic population, and hydraulic and hydrologic factors such as depth, velocity, and bed material would be assumed. The carbon budget would be modeled to explore the importance of organic matter nutrients and sediment.

Soil Losses

3. Continuing research is needed to develop better understanding of the soil erodibility factor K for U.S. soils. K factors are especially

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needed for disturbed land such as strip-mine spoil and subsoils.

4. Studies should be made to determine more accurately the rainfall factor R for mountainous areas of the United States where rainfall is highly variable at different altitudes and is affected greatly by orographic effects of mountains.

5. Further exploration is needed as to the variability of drop size in rainfall in the United States and the effect of drop size on the rainfall factor R in the USLE.

Stream Sediment

6. Some of the planning models described in this report need to be tested to demonstrate their strengths, capabilities, and limitations. The ANSWERS and the LANDRUN models should be tested on a number of watersheds to check their sediment predictions.

7. The ARM model, although it is complex, should be further tested and developed. It accommodates budgets of nutrients and other pollutant materials not available in ANSWERS or LANDRUN.

8. When the 1979 SEA-AR field-scale sediment planning model becomes available, it should be exercised, calibrated, and used to evaluate stream sediment as well as nutrient budgets in various locations.

9. It would be highly fruitful to carry out applied research to calibrate some of the complex research models described herein. Detailed data from existing watersheds should be assembled. The models of Neibling and Foster (1977); of Li, Simon, and Shiao (1977); and of Smith (1976) should be used to predict stream sediment. The results would begin to show the quality of our current understanding of the soil detachment, transport, and deposition processes that govern our prediction of stream sediment. This research would also help to focus attention on the processes for which we need better understanding and on the scope of data needs required for better planning models.

10. Research is needed to study the particle-size characteristics of upland soils and stream sediments. What are the particle-size distributions actually found in streams? To what extent do soil and sediments move as aggregates? What are the physical and chemical properties that govern the formation and stability of aggregates?

11. Studies are needed of the chemical and physical relations among soil particles, aggregates, organic matter, various nutrients such as N and P, and other chemical constituents. Involved would be the chemistry and physical attributes of the water, clays, colloids, and chemical elements. Other recommendations are discussed by Robinson and Renard (1977).

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Upland Farming Practices

12. Studies are needed to document whether upland soil conservation practices reduce sediment in downstream streams or lakes. It would be valuable to compile some case studies to show whether upstream soil-conservation practices reduce sediment yield downstream. Stall made such a study (1962), but much more documentation is desirable. Projects should be located where extensive soil-conservation measures have been installed on a watershed and downstream sediment has been monitored. After the project, the impact on sediment yield should be analyzed.

13. An elaborate, broad-based, well-designed research effort should be initiated to use a sophisticated sediment-research model, such as one of those described in item 9, to calculate upland soil loss and resulting stream sediment for a selected specified set of existing farming conditions. A field-size area of perhaps 40 acres would be used. Various upland conservation practices such as use of contours, terraces, grassed waterways, and minimum tillage or combinations of these practices would then be modeled and their effect on stream sediment would be modeled and evaluated.*

Linking Upstream and Downstream Physical Processes

14. In spite of the limitations on existing planning models, it would be useful to model the upstream-downstream relationship between land use and water quality by linking a planning model such as ANSWERS or LANDRUN to a stream-processes model which routes runoff and sediment (for example, Williams, 1975a, routing model).

Land Resource Areas within each Water Resource Region

15. Research should be carried out to evaluate the effectiveness of nonincised channels in trapping eroded soil. This one parameter, the length of nonincised channels in the watershed, holds promise of explaining the differences between known upland soil losses and stream sediment. Actual watersheds could be selected where upland soil losses could be calculated and where downstream sediment yield has been measured over a period of years in a reservoir or by a sediment-gauging station. The length or density of nonincised channels could be determined by field mapping.

16. Research is needed to develop a much better understanding of the flow of sediment-laden water through grass. Theoretical calculations could be made of flow conditions. A study could be made of the performance and problems of real grassed waterways that have been functioning for several years. What are the design criteria and what is the expected performance of a greenbelt area established along a stream? How does the greenbelt affect the movement of upland soil loss into the stream?

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*The USEPA is currently undertaking such a project with the Iowa Field Evaluation Project.

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17. Unit stream power should be studied throughout a stream system in order to evaluate the means through which the stream adjusts its energy expenditure. This energy system governs transport of sediment and erosion or deposition in the stream system. Understanding this energy system could reveal differences in the energy regimen between streams, which difference could absolutely govern the downstream delivery of sediment. For basin-scale watersheds, say 2590 sq km (1000 sq mi), the USP might provide the linkage between upstream and downstream sediment. About 6 to 12 basin-size stream systems could be evaluated and compared by their USP. This power would be related to upstream soil loss calculated by the USLE, and downstream sediment could be measured at a stream gauging station.

Linking Models of Land Use to Models of Physical Processes

There are two basic approaches to linking models of land management and physical processes. The first approach is to incorporate land-management and physical-processes models into one large mathematical model that determines land-management patterns and water-quality parameters simultaneously. The second approach is to keep the land-management and physical-processes models separate. The land-management model would generate a land-management pattern and a set of parameters or coefficients that would be input to the physical-processes model, which would then be run to determine water-quality parameters. Through an iterative process, the desired water-quality solution can be attained. The primary advantage of incorporating the land-management and physical-processes models into one large mathematical model is that a land-management plan can be developed in direct response to water-quality goals rather than going through a time-consuming, trial-and-error process. It will be difficult to combine mathematical programming models of land management and the more sophisticated physical processes models into one large programming model where land management is directly restricted by a water quality goal. Either of these approaches could provide valuable information to planners and politicians in that a more complete specification of the impact of alternatives would be available.

Land-Management Component

The purpose of this component is to enable the evaluation of alternative land-management plans for further consideration in the planning process. Other objectives besides improving water quality could be considered in land-management planning. SWCDs, which will probably play an important role in the planning process, could consider secondary goals such as increasing crop production, maintaining soil fertility, assisting landowners in planting trees and managing woodlots, and providing wildlife habitat. Practices that could serve more than one objective should be selected when possible.

Although it is not necessary to build models of land management because land managers could use their professional judgment to develop plans, there are a number of advantages to using mathematical models. More aspects of a problem can be included into a computer model. More alternatives can be

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explored because it is usually cheaper and quicker to develop alternatives once a model has been built than to develop plans without the aid of models. Thus, a wider range of possibilities could be explored and more detailed information on the economic impacts of the alternatives could be estimated if costs, prices, and economic relationships are included. The models could then be helpful in finding cost-effective alternatives to improve water quality. Professional judgment, however, could be applied to eliminate or change alternatives that appear to be infeasible because of factors not included in the model. Professionals could use land-management plans developed by mathematical models as aids for the development of actual plans to be recommended.

A land-management model should predict crop production and agricultural land management, including crop rotations, conservation practices, and tillage practices, fertilizers, pesticides, costs, and revenues. Constraints on crop production or land management could be included to achieve conformity to existing patterns. Ideally the model should allow for consideration of structural and any other practices available to control runoff, chemical losses, and all forms of erosion including sheet-and-rill, gulley, and streambank erosion as well as changes in land use. Management of rural, nonagricultural land such as woodlots and unfarmed fields should also be included. Such management, however, might be less important because, in many cases, those fields would not contain significant sources of pollution. Onsite damages (or benefits) resulting from (the control of) soil loss and plant-nutrient losses should also be estimated. A land-management model should be able to generate input for the physical model used. It should also be able to accommodate policies that might be used to control pollution, policies such as cost sharing, taxes, and restrictions on pollution loading and land-management practices. In addition, problems such as noncompliance that are likely to be encountered in implementing a program ought to be considered when one estimates what water quality would result when a program is implemented. Sensitivity analysis could be used to study the impact of uncertain parameters of water-quality relations on land-management plans with both approaches to linking land-management and physical models.

Several general approaches to modeling a land-management component include: linear-optimization models, nonlinear-optimization models, and nonoptimizing or simulation models.

Linear-Optimization Models

Linear programming is traditionally applied to agricultural land-management problems, including some applications to water-quality problems. Many linear programs are implemented at the watershed level (Alt, Miranowski, and Heady, 1979; Jacobs and Timmons, 1974; Kasal, 1976; Sharpe and Berkowitz, 1979; and White and Partenheimer, 1979). Others are implemented at the national or subnational level (Osteen and Seitz, 1978; Taylor and Frohberg, 1977; and Wade and Heady, 1977). When one considers programs implemented at the national or large subnational levels, he should take into account the impacts of programs on crop prices, whereas this provision is not necessary at the small watershed level. At the watershed level, farm or regional income could be maximized, assuming constant prices, subject to constraints that certain levels of crop production, land management, and levels of onsite

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pollution loadings (or water quality under certain formulations) be met. Given the state of the art of modeling physical processes, currently one could model only very small watersheds when linking models of land management and the more sophisticated physical-processes models. Hence, constant prices for commodities could be assumed. One must keep in mind, however, that large-scale changes in land management, particularly in crop production, can have impacts on crop prices and farm income. In addition, planners might want to study the impacts of different nonmonetary priorities for outputs of land-management plans. In such a case, goal programming, a form of linear programming, would be an appropriate technique. It would require an objective function with units of production weighted to meet production goals, thus minimizing weighted deviations from production goals. As a result, production goals would not have to be met (Field, 1973). Goal-programming algorithms are available. Impacts on farm income of alternative land-management plans could be summed in an accounting row. Goal programming and profit- or income-maximization formulations could be built into the same linear-programming tableau.

The great advantage of linear programming is that algorithms are widely available and knowledge of the technique is widespread. A major problem, however, is that the nonadditive pattern effects of land management cannot be considered (Patterson, 1972). Even with the same acreages of land management practices on a farm or field, differing the spatial allocation could impact runoff, erosion, or other variables such as wildlife habitat. Linear programming would not be able to account for such interactions. If these patterns were known it would be possible to constrain the model to require these land-management patterns while allowing the model to allocate other land-management practices.

Nonlinear Optimization Models and Simulation

There are two alternative approaches to linear programming, economic, land-management models: non-linear programming and simulation (non-optimizing models). No applications of these two approaches to water quality management have been found by the authors. Nonlinear optimization techniques would be useful where there are interactions between land management practices or nonlinear water quality relationships could be stated. It is conceivable that the applications of such models to water quality problems could be difficult and expensive to solve.

Simulation Models

Simulation models could also be used for economic models of land management. It is difficult to generalize about simulation models because they can take so many different forms. A simple simulation model could develop budgets, crop production, and water quality impacts of land management plans. They have not been applied to nonpoint-source pollution-control problems to any great extent. The value of simulation models for nonpoint-source pollution-control problems will depend upon the quality of the economic relationships and decision rules included in the model. A well-constructed simulation model might be able to overcome the limitations of the basic assumptions of linear programming and be able to predict landowner responses

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to various incentive programs more accurately. Simulation models may also be cheaper to run than linear-programming models, so more land-management alternatives could be explored. The basic disadvantage is that developing such a model could be quite expensive. It is, however, an alternative approach to linear programming for land-management modeling and is worth considering in the future.

The Method of Linking Land Management to Watershed Models

In this section of the report, the method of linking land management models to watershed models such as empirical methods, LANDRUN, ANSWERS, ARM, and SEA-AR is investigated. The situations where models of land management and of physical processes can be incorporated into one mathematical model that simultaneously determines land-management plans and water-quality parameters will be identified. Situations in which the models of land management and physical processes must be run separately will also be identified. The sediment-related water-quality parameters that will be considered in this section will be the total quantity of sediment moved into the stream and the duration curve of suspended sediment. The total quantity of sediment can then be related to damages associated with the silting in of reservoirs and drainage ditches and the covering of spawning beds of aquatic animals. The duration curve of suspended sediment can, thus, in the latter case, be related to reductions in fish populations.

The emphasis of this section will be on linking physical-processes models to linear-programming land-management models. With linear-programming models, it would be advantageous to include directly into the linear-programming matrix constraints on sediment delivered or suspended sediment because one could relate a land-management pattern directly to water-quality goals rather than going through a trial-and-error process to find a satisfactory plan. The question of whether physical-processes models should be incorporated into one large model with a simulation or nonoptimizing model of land management is not particularly interesting because it is unlikely that the information necessary to accomplish the task is available. The simulation model will not develop an "optimal" solution of land management in response to water-quality constraints. Hence, a trial-and-error process of some sort is probably required. Whether a land management simulation model and a physical-processes model should be run together or separately is primarily a matter of convenience.

Only two physical-processes models considered in this report can be incorporated directly into a linear-programming matrix: the empirical models developed by Williams (1975b) and by Simons, *et al.* (1977). When a runoff model which assumes that runoff is not changed by changes in land management is used, the hydrograph of each design storm would not change when the pattern of land management changed. Sediment delivered, however, would change because the crop-practice factors of the USLE would change. Total sediment delivered and the sediment duration curve could be modified with each land-management pattern without including the hydrologic model into the linear program.

The modeling procedure would begin by making a baseline run of the

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land-management linear-programming model with no constraints on sediment to determine a land-management pattern and a set of economic parameters for comparison with later runs of the model. Coefficients for the empirical model would be derived from the baseline land-management pattern. The physical-processes model would be run for each design storm determining total sediment moved, the storm hydrograph, and the storm sediment graph (Williams, 1978). From the series of hydrographs and sediment graphs derived for each storm, a suspended-sediment duration curve can be defined for the series of design storms. This procedure requires the assumption that the sediment moved during a storm is primarily washload transported in a suspended state. This assumption appears to be legitimate for the Midwestern agricultural region.

The farm-management model could then be optimized, subject to constraints on total sediment, to study the impacts on land management and costs. The "optimal" land management to meet water-quality goals would be determined by minimizing opportunity cost as defined by the objective function. The sediment duration curve can be modified for each land-management pattern without including the hydrologic model in the linear-programming matrix. Only the C and P factors would change. Hence, the sediment duration curve would be rotated around the intercept of the time axis, but the basic shape would not change. The constraint on total sediment moved could easily be included in the model with the following inequality:

$$\sum_i \sum_j A_{ij} X_{ij} \leq Y_a \qquad \text{(Eq. 14)}$$

where

Y_a = goal for total sediment delivered over a certain period of time to a point in the watershed. (Y can also be an average sediment yield per unit of time.)

X_{ij} = acreage of land practice i (a combination of rotation and tillage and conservation practices) on soil j.

A_{ij} = sediment delivered per acre with practice i on soil j.

$$= \frac{Y_b \cdot C_{ij} \cdot P_{ij}}{X \cdot C^b_{ij} \cdot P^b_{ij}}$$

C_{ij} = USLE cropping factor for practice i on soil j

P_{ij} = USLE practice factor for practice i on soil j

C^b_{ij} = cropping factor under baseline conditions for soil j

P^b_{ij} = practice factor under baseline conditions for soil j

Y_b = sediment yield under baseline conditions (could also be an average per unit of time)

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X = acreage of entire watershed above the point in the watershed where the goal is set

Constraints on total sediment delivered for a number of points in the waterway could be included in the model, if desired.

Constraints on suspended sediment could also be included in the model. The goal would be stated such that suspended sediment would not exceed a given concentration more than a certain percent of the time. The constraint would affect all area upstream and would take the following form:

$$\sum_i \sum_j B_{ij} X_{ij} \leq Z_{an} \qquad \text{(Eq. 15)}$$

where:

Z_{an} = suspended sediment goal; suspended sediment would not exceed this quantity n percent of the time

B_{ij} = suspended sediment per acre n percent of the time with practice i on soil type j

$$B_{ij} = \frac{Z_{bn} \cdot C_{ij} \cdot P_{ij}}{X \cdot C^{b}_{ij} \cdot P^{b}_{ij}}$$

Z_{bn} = suspended sediment under baseline conditions that are exceeded n percent of time

Accounting rows with coefficients similar to B_{ij} in Equation 15 could also be included to compute the new sediment concentration for a number of different duration probabilities. In this way, the suspended-sediment duration curve for the new land-management pattern could be constructed. Constraints on suspended sediment could be applied in this same way at different locations in the waterway. It is likely that only one of the locations would actually restrict the solution since all locations will be closely related.

There are a number of situations where combining physical-processes models and linear-programming land-management models into one large linear program will be difficult, if not impossible. If the hydrologic relationships of the physical-processes model are affected by land management so that the volume of runoff, the peak flow, or the shape of the hydrograph is changed, the land-management linear-programming model and the physical-processes model will generally have to be run separately. Under these circumstances, interactions among variables determined in the model will violate the basic linear-programming assumption of additivity and independence of variables. The cost of running a physical model and its size may also make it difficult to combine a physical-processes model and a land-management linear-programming into one large linear-programming model.

When the model assumes that volume of runoff, the peak flow, or the

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shape of the hydrograph is affected by land management, the runoff and sedimentation models would have to be made a part of the linear-programming matrix. A simple modification of the baseline runoff and sedimentation conditions using the previously described methods could not be made. Both sediment and runoff variables would have to be determined in the linear-programming matrix, which would create problems for LANDRUN, ARM, ANSWERS, the Williams empirical model (when runoff is affected by land management), and, probably SEA-AR. In all of these cases, the basic linear-programming assumption of additivity and independence of variables would be violated. With the Williams empirical method and LANDRUN, the runoff factor would have to be determined within the linear-programming matrix. The runoff factor is determined by the product of peak flow and total runoff. The product is input to an exponential function which, in turn, would be multiplied by the acreage of a given practice. This series of operations violates the assumptions of linear programming because variables determined within the model cannot be multiplied together or taken to the nth power. Hence, LANDRUN and the Williams empirical method (when runoff is affected by land management) cannot be incorporated into a linear-programming matrix.

Similar problems occur with ARM and ANSWERS. With the ARM model, total runoff would be determined within the linear-programming matrix and would be input to an exponential function. Also, sediment transported by overland flow is multiplied by the fraction of runoff reaching the stream. Both of these variables would have to be determined within the linear-programming model. These computations would violate the assumption of additivity of variables. With the ANSWERS model, volume of flow enters a relationship that determines flow detachment of sediment. In this relationship, the cropping factor C of the USLE is multiplied by the flow rate. Unless each land unit in the ANSWERS model is restricted to one cropping practice, the acreage of each practice applied would be needed to compute a weighted average of the C factor. Hence, the acreage of each practice and flow, both determined in the linear-programming matrix, would be multiplied together. The assumption of additivity and independence of variables would be violated. If each land unit of the ANSWERS model were restricted to one practice, integer programming would be necessary for the land-management model. The specifics of the SEA-AR model have not been released as of this writing. It seems likely, however, that this model would also violate the assumptions of additivity and independence of variables because its hydrology and sedimentation relationships are similar to those in ANSWERS.

These five approaches could not be included in a large linear-programming matrix not only because they are theoretically inconsistent with linear programming but also for a number of practical reasons. Both ARM and SEA-AR are continuous simulation models. The physical-processes model would have to simulate the entire time period for each iteration of the linear-programming model, which would be a very expensive operation because linear programming can iterate many times. Running ARM, in particular, is rather expensive, so running it for every iteration of a linear-programming model would be impractical. Also, the number of time intervals that would have to be considered by the ARM model would require so many rows in a linear-programming model that the cost would be prohibitive. ANSWERS, LANDRUN, and the Williams empirical model when runoff is affected by land management would require that the hydrology model be run for every design storm for every iteration of the linear-programming model, which would be extremely expensive.

Because the land-management linear program and the more sophisticated physical-processes models must be run separately, the next problem is to determine the type of linkage between them. A set of land-management alternatives would first be developed by the land-management model. Each land-management plan would define a set of coefficients for the physical-processes model, which would then be run to estimate the pollution loading parameters associated with the plan. An important consideration is that the land-management model be able to provide the coefficients used in the physical-processes model as a printed output. USLE factors weighted by the area of practice could be computed for the watershed or a portion of the watershed in accounting rows and provided as printed output. In fact, any computation that does not violate the assumption of linear programming could be performed in accounting rows to provide coefficients for the physical-processes model. All of the physical-processes models considered as planning models in this report use USLE-type input.

The first step in this iterative procedure would be to estimate current land management practices. The physical processes model would be run to estimate the pollution loading parameters associated with the current land management pattern. The impacts of land management alternatives could be compared with these baseline conditions. The next step would be to develop a set of alternatives to the current pattern of land management. Various constraints corresponding to alternative erosion- and sedimentation-control policies as well as constraints for other land-management goals would be included in the land-management model to develop a set of alternatives for further consideration. Constraints with respect to erosion and sedimentation would include: (1) restrictions on soil loss per acre or per larger areas as computed by the USLE, (2) restrictions on sediment yield as computed by the USLE modified by a delivery ratio, or (3) restrictions on sediment yield on suspended-sediment concentration as computed by the Williams empirical method when runoff is not affected by land management. The method used to constrain suspended sediment would be the method discussed earlier in this section (Eq. 15). The land-management model could be constrained to different levels of sediment yield or concentration to develop different land-management plans. Other policies such as restrictions on land-management practices, cost sharing, subsidies, or soil-loss taxes could also be used to develop land-management alternatives. Once this initial set of alternatives was developed, those with "unacceptable" impacts could be eliminated. Criteria for eliminating alternatives could include: (1) the unacceptability of certain policy tools to the public, (2) the lack of available resources to implement alternatives, and (3) the unacceptable concentration of an impact on a certain group of people.

Once a set of land management alternatives has been developed, land management coefficients for the physical-processes model would be obtained from the land-management model. Pollution-loading parameters for each alternative would then be developed. Those results could then be compared to the pollution goals developed for the watershed. If the results of a particular

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alternative did not meet the water-quality goals yet seemed to be promising enough for further consideration, the alternative would have to be modified and rerun, until it met the water-quality goals. Professional judgment could be used to concentrate changes in land management to those areas which would bring about the greatest changes in water quality in order to minimize the trial-and-error aspects of this process. New constraints could also be applied to the land-management model to modify alternatives. When a number of alternative land-management plans had been developed to meet alternative water-quality goals, the impacts on water quality, land management, and economics, would be displayed for the interested public to investigate.

This type of iterative approach to defining and choosing alternatives might not find the global optimum for the system. It might, however, suggest significant improvements over the current situation by allowing a choice of implementable alternatives. Ultimately, the water-quality goals and a land-management plan would be chosen after public scrutiny and discussion between resource-management professionals and the interested public. This approach would be oriented toward finding a politically acceptable approach that would improve water quality rather than defining some global-optimum solution.

Finally, we will briefly summarize the advantages and disadvantages of the two approaches to linking a land-management linear-programming model to a physical-processes model. The main advantage to being able to incorporate these two models into one linear-programming matrix is that a land-management plan can be developed in direct response to water-quality goals without going through an extended trial-and-error process. Because of the simplicity of the physical-processes model required, this approach would probably be inexpensive. The main disadvantage, however, is that the simple hydrologic models and the empirical methods of determining sedimentation are considered to be less realistic than the more sophisticated models, particularly ARM and ANSWERS. The main advantage of running the land-management model and the physical-processes model separately is that the more sophisticated physical-processes models could be used. Hence, the predictions of water-quality parameters associated with a land-management plan might be more accurate and realistic. The disadvantages of this approach are that a fairly time-consuming, trial-and-error process might be required. The time involved and the cost of running the more sophisticated physical-processes model would make this approach relatively expensive.

The main trade-off between running the land-management and physical-processes models as one model or separately is accuracy and realism versus cost and convenience. Running the models separately may produce more accurate results but is costly and inconvenient, while running the models together is less accurate but also cheap and convenient. The need for accuracy and realism in the ISWQM planning process appears to mandate the approach of running a physical-processes model and a land-management model separately. This conclusion, however, is not firm. Both approaches to linking land-management and physical-processes models really need to be implemented on a number of watersheds and compared to each watershed's actual behavior. The differences in accuracy and realism of results and the differences in costs need to be determined to better define the trade-offs between the two approaches. A more realistic assessment of the trade-offs is needed to enable one to make a better choice between the two approaches.

A RECOMMENDED DECISION-MODEL STRUCTURE FOR THE ISWQM APPROACH

What Information Should the Model Provide?

The model of the decision system should provide information to help make decisions about what water-quality goals to choose and how to manage resources to pursue those goals. The model of the decision system needs to provide information useful for making comparisons among alternative courses of action with respect to such criteria as physical and biological feasibility, economic efficiency, equity, political and cultural acceptability, and operational or administrative practicality (Clawson, 1975). A discussion of some of the different types of information a decision model should provide and some of the assumptions that could be used follows:

1. Water-quality parameters estimated by the model need to be related to water-quality goals or pollution damages. Total sediment moved can fill reservoirs and channels and, hence, can have impacts on drainage, water-supply capacity, recreation, commercial navigation, and fish habitat. Suspended sediment can have impacts on fish populations and species. Alternative water-quality goals should be developed and then considered by the decision model, which will develop land-management alternatives to meet each set of water-quality goals. The benefits and costs of achieving each alternative set of water-quality goals should be estimated and then displayed for the consideration of professionals and the interested public. Planners could thus choose water-use and water-quality goals and a land-management plan while remaining aware of the suggestions and preferences of the public.

2. The model should allow for the consideration of a wide variety of crop-production and pollution-control practices. While the first priority in model development should be crop production, the model should also consider other agricultural land uses such as grazing or forage, forest-crop production (such as trees and nuts) and wildlife management. The agronomic crop-production portion of the model should be able to consider crop rotation, tillage practices, conservation practices, and such off-the-field erosion- and runoff-control practices as field borders, grassed waterways, and greenbelts along streams. Whether or not practices such as field borders, grassed waterways, and greenbelts can be considered depends on the state of development of physical processes models.

3. The model, ideally, should be able to define a number of economic variables useful to analyzing economic efficiency and equity, such as the production of crops and other market and nonmarket outputs, net income, and the capital and operating costs of pollution-control practices. The objective of the decision model should be to determine the opportunity costs and equity implications of pursuing

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different courses of action. Because of the restrictions on the size of watersheds of the physical-processes models, the impacts of changes in crop production on crop prices can be ignored. The equity analysis should consider the income impacts on different groups of people (such as the owners of different types of land) and the impacts of changes in the production of nonmarket commodities on the people who consume them. These efficiency and equity impacts will affect the cultural acceptibility and operational practicality of an alternative.

4. The decision model should be able to estimate both total sediment moved to a point (or points) in a stream and the concentration of suspended sediment. The model should also be able to determine the impacts of nonpoint-source pollution-control practices on these two parameters by considering their impacts on soil detachment, runoff, and the delivery of soil to a waterway. The impacts of incised and nonincised channels, concavity of slope, and vegetative strips on sediment delivery to streams need to be considered in the future development of physical processes models.

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In the Midwest, wash load and bed load move in separate regimes within streams. Hence, they can be treated separately in modeling stream processes. Bed load, in the Midwest, appears to be of minor significance in causing sediment damages, so it can be left out of the model without causing a large error in calculating sediment damages. As a result the model can concentrate on wash load, which is, to a large extent, controlled by upland processes. In the Midwest, upland soil particles are fine and move primarily as wash load. Wash load can be deposited in pools during low flow periods and scoured out in storms, thus complicating stream processes. Currently this process of deposition and scouring probably cannot be modeled in a land-management water-quality model. In addition, sedimentation and runoff processes should be related to the movement of other pollutants such as nutrients and pesticides.

The Recommended Model Structure

Early in any ISWQM planning study, alternative water-use and water-quality goals, alternative approaches to managing nonpoint-source pollution, criteria to be addressed in a benefit-cost analysis, and criteria for eliminating alternatives at later stages in the study need to be defined. With an actual planning study, public opinion and professional judgment need to be integrated in making these determinations. With a research study conducted to test methods or examine issues, however, public involvement is not necessary. Quantitative models may be useful in addressing water-use and water-quality goals. Quantitative methods are not applicable for choosing criteria or determining alternative policy approaches for consideration.

Estimating demand functions for all potential uses of a stream would be a useful way to address water-use and water-quality goals from an economic point of view. Estimating demand functions is not necessary because defining and choosing among alternative goals are ultimately political. Rather, a

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series of alternative goals could be developed for consideration by integrating public opinion and professional judgment without using demand functions. Demand functions would be useful because they could estimate the number of different water uses demanded under different situations and the water-use benefits received (or damages incurred) under alternative water-quality goals. The advantages of demand functions must be compared with the costs of estimation when deciding whether to use them. The use of demand functions would seem to be most appropriate on waterways where there are complex trade-offs among uses and difficult choices to make. Under such situations, good information about the implications of choices would be very desirable.

If the decision is made to develop demand functions for uses, different approaches may be required for different uses. Estimating demand functions for transportation uses, recreation occurring on easily definable sites, and some consumptive uses of water, such as municipal or industrial uses, will be easier than estimating demand function for other uses. The necessary data for these uses can be obtained without much trouble. It will be more difficult and expensive, however, to develop demand functions for recreation activities that are not confined to a specific site. Fishing, for example, can occur throughout a watershed, making it difficult to define the population to be sampled. In such situations, demand could be estimated over a large area. The quantity of demand could then be allocated to individual waterways, recognizing priorities of uses and the suitability of waterways for uses. The value determined for the use over the large area could be used to estimate benefits and damages on the individual waterway. It will probably be difficult to estimate demand functions for such intangible values as esthetics because of the difficulties involved in measuring changes in esthetics and relating them to monetary values. Hence, it may be more reasonable to indicate a goal to provide a more or less esthetically pleasing experience under an alternative or indicate that an alternative will provide a more or less esthetically pleasing experience as compared to some other alternative.

Once alternative sets of water-use goals are determined for consideration, water-quality criteria must be defined. Water-quality criteria can be used to determine water-quality standards or to help measure benefits and costs associated with an alternative. Water-quality criteria for a number of water uses have been defined and could be used in ISWQM planning studies. The list of water-quality criteria is incomplete, however. For example, criteria for suspended-sediment concentration have not been defined for most uses. Criteria often have not been developed for different species of fish. The latter are important because changes in water quality can change total fish production and species composition, thus affecting the use of the stream. More research is needed concerning the effects of water-quality parameters on uses to expand the list of criteria. This research could be expensive and could take a long time. In the meantime, the existing list of water-quality criteria should be used whenever possible. It may be necessary to use professional judgment, some of which might not be supported with published research, to modify existing criteria, to suggest new criteria, or to identify factors limiting the improvement of a stream for different uses. Given the subjective nature of this approach to defining criteria, such criteria should be subjected to professional debate so that their strengths and weaknesses will be more fully understood. Particularly controversial criteria could be removed or changed.

The approach to linking models of land management and physical processes is to run them separately so that the more sophisticated, physical-processes models can be used. The recommended land-management model consists of a farm-management linear program for a small watershed. (A simulation model could be a reasonable substitute.) The model should estimate crop production, crop rotation, tillage and conservation practices, soil loss, and any other land-management and pollution-loading parameters needed for the physical-processes model used. The model should also estimate profits for the watershed and different classes of land to estimate the opportunity cost and distributional impacts of different parameters. The objective function for the model should be the maximum of farm income with crop prices held constant because of the small area being considered. Constraints on land management and crop production could be applied to the model to simulate current conditions.

The land-management model should be constructed so that it can handle the policy approaches developed in the planning study. Such policy approaches could include restrictions on soil loss, agricultural chemical applications, or land-management practices. Other policy approaches include taxes or subsidies on soil loss, agricultural chemical application, or land-management practices. The model could include relationships to determine total sediment moved and the sediment graph at a point in the stream using the Williams empirical method assuming that runoff does not change with land management. These relationships could be used to provide the first-cut approximation of how land should be managed to meet goals for sediment control. This approach would help to reduce the number of runs in the iterative process associated with running physical-processes and land-management models separately. Once the agricultural portion of the model has been constructed, management of rural land not in agronomic crops could be modeled. Since SWCDs will probably play an important role in nonpoint-source pollution control, the interrelationships between nonpoint-source pollution control and other noncrop production-related objectives such as timber and fiber production and wildlife habitat should be studied.

ANSWERS, ARM, and the SEA-AR model would all be good choices for the physical-processes model. They are all fairly sophisticated but have reasonable information requirements. If the planning study is to be primarily concerned with sediment problems, ANSWERS would probably be the best choice because of its treatment of sediment processes. Also, because it is a distributed model and is based upon a grid system to account for land variations, it is better suited for looking at the impacts of changing land-management patterns than the other point models. ANSWERS also handles larger areas than the other models, but it is still a small watershed model. The ARM and SEA-AR models are better choices if the planning study is to be concerned with agricultural chemicals as well as sediment problems. ARM and SEA-AR contain relationships to predict concentrations of agricultural chemicals while ANSWERS does not. The ANSWERS model would have to be modified to include relationships to predict the behavior of agricultural chemicals before it would be useful in studies where the emphasis would be on nutrient and/or pesticide problems.

Once a modeling system has been developed, a land-management alternative must be evaluated for each alternative set of goals. When the physical-processes and land-management models are run separately, land-management patterns cannot be developed by constraining the modeling system with water-quality goals. Hence, an iterative process would be needed to develop a land-management pattern. This iterative process might not find the global-optimum solution to maximize farm income subject to constraints. It may be a useful method, however, to develop a set of alternatives for further consideration.

The iterative process of evaluating alternatives begins by running the land-management model with no environmental constraints and then running the physical-processes model to estimate water quality under baseline conditions. Plans to control nonpoint-source pollution are developed by constraining the land-management model or adjusting the model coefficients in accordance with an alternative water quality goal. Such changes in the land-management model could include financial incentives for certain practices or restrictions on soil loss, fertilizer application, or sediment concentration as computed by the Williams empirical method when assuming that runoff does not change with land management. The land-management model is then run subject to the constraints or changes in coefficients. The results of the land-management model define the parameters needed to run the physical-processes model, which estimates water-quality parameters.

If the estimated water-quality parameters should diverge from the water-quality goals by more than some predetermined amount, the land-management plan would have to be changed and the model rerun. If the estimated water-quality parameters should exceed water-quality goals, the land-management model could be changed by increasing financial incentives, making the environmental restrictions more restrictive, or constraining the model according to some external change in the land-management pattern. If the estimated water-quality parameters were less than the water-quality goals, the land-management model could be changed to relax financial incentives or environmental restrictions. Both the land-management and physical-processes models would be rerun to determine a new land-management pattern and estimate water-quality parameters. This iterative process would be continued until water quality goals were met. This process could also be used to develop a series of more and more restrictive alternatives of the same policy approach.

As stated earlier, criteria to reject alternatives could be developed. If, in the process of developing an alternative, it appeared that the alternative should be rejected, the process of developing it could be stopped to save time and money. Criteria for rejection of an alternative could include an excessive opportunity cost or undesirable distributional impact.

Once the development of alternative goals and land-management plans was completed, a benefit-cost analysis of each alternative would be needed so that the strengths and weaknesses of all alternatives could be compared. Criteria for comparison could include economic efficiency, equity, political

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and cultural acceptability, and operational practicality (Clawson, 1975). One alternative set of goals and a land-management pattern should be chosen for implementation. Both professional judgment and public opinion should be considered when a choice of alternative is made. The alternative finally chosen could be one of those designated for consideration or could be a new one developed in light of the analysis of alternatives.

CONCLUSION: HOW FEASIBLE IS ISWQM AS COMPARED TO SOURCE CONTROL?

The source-control approach to water quality management is currently feasible, an example being the soil-conservation program. Economic and physical models are readily available for use under this approach. Institutions to implement such an approach on agricultural lands already exist. Some changes in existing institutions, specifically SWCDs, would likely be desirable: (1) A role in planning land management should be provided for people living outside of the boundaries of an SWCD who have an interest in the impact of the management of land within the SWCD on water quality. (2) Nonlandowners should be allowed to vote in elections concerning land-use regulations. (3) Urban residents should be brought into the planning process. These changes in institutions, however, could require changes in state soil and conservation laws, a process that could be time-consuming and could encounter political resistance.

ISWQM encounters more problems than source control because the costs and technical problems of implementation and political resistance to implementation would be greater. It would not, however, be impossible to implement ISWQM.

Institutional changes are needed for ISWQM in addition to those outlined for source control. A closer integration of land management and water-use and water-quality goals is needed for ISWQM than for source control. Agencies managing waterways, defining water uses, defining water-quality goals, and developing land-management plans need to work more closely together in the ISWQM planning process than under source control. It would be desirable, but not necessary, to clarify the roles of agencies involved in the water-resources planning and management process to eliminate overlapping responsibilities. In addition, the plans of local governments located within the same watershed need to be coordinated so that their goals and land-management plans do not conflict. As part of the ISWQM planning process, there should be a feedback mechanism to evaluate the progress of the plan in terms of meeting goals and to periodically reassess the goals and plans.

The creation of nonlocal coordinating agencies, such as 208 planning agencies, would provide the changes needed in institutions and the planning process for ISWQM. These agencies will require some legal powers to coordinate the activities of SWCDs. Such agencies could make the implementation of ISWQM more difficult than source control, which already has in place institutions to implement the program. There would probably be political resistance to giving a coordinating agency a role in local decision making. The more power proposed for the coordinating agency to develop and implement plans, the greater the political resistance would probably be. Another

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problem would be the cost of funding the coordinating agency. The implementation of ISWQM would thus be more difficult than source control because of these institutional problems.

There are a number of technical difficulties for developing land and water-resource plans under ISWQM. While defining water use goals is a political process and demand functions would not have to be estimated, demand functions would be useful in estimating the quantities of uses desired and the benefits (damages foregone) associated with different management alternatives. If demand functions are estimated, the necessary costs and time involved in estimation would have to be incurred.

Lists of water-quality criteria have already been developed and could be used to define water-quality goals for uses. The lists are incomplete, however. Criteria have not been developed for sediment and other pollutants. Some criteria refer only to more general uses when more specific breakdowns might be desirable. For example, a criterion might be developed for wildlife and fish propagation, but a criterion for a specific fish species or equatic ecosystem might be desirable but unavailable. Research to estimate values for these criteria would be time-consuming and expensive. Waiting for more complete lists of water-quality criteria to be developed would preclude implementation of ISWQM in the foreseeable future. The alternative would be to use professional judgment to modify the values of existing criteria, suggest values for criteria for uses and pollutants for which no values are currently defined, or to identify factors limiting the provision of a use without defining a numerical value for criteria. This judgment could serve to identify the most important water-quality problems in meeting water-use goals. Such an identification would reduce the wasteful allocation of resources to control nonpoint-source pollutants that are not limiting factors to providing desired water uses. Values for criteria that are developed using professional judgment could evolve into an accepted standard through further research or experience that indicates how changes in water-quality parameters affect uses.

There are no particular problems for the implementation of ISWQM in the area of land-management modeling. Land-management models have been developed that could be applied to a ISWQM study, but more realistic models would be desirable. There is also a need to develop a better understanding of the impacts of agricultural land management on noncrop production values.

Modeling the land-management/water-quality relationships is the biggest technical problem in applying the ISWQM. A number of planning models of physical processes can estimate the movement of water, soils, and agricultural chemicals from a farmer's field to a stream. They can be used to estimate total sediment delivered, sediment concentration, and agricultural chemical concentrations in the water. All of the physical-processes models have strengths and weaknesses. The more sophisticated models require an iterative procedure to develop land-management plans when they are linked to a land-management model. Stream processes models that can be linked to these physical-processes models are in early stages of development. In particular the behavior of washload and its impact on suspended sediment is poorly understood. All of the more sophisticated models are restricted to

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small watersheds. For larger watersheds, the general approach has been to determine water-quality problems and sources of the problem to concentrate on. As an alternative, small watersheds within a large watershed could be sampled for development of land-management plans. Guidelines determined in these land-management plans could be applied to other parts of the large watershed having similar characteristics. As a result of these technical problems, applying ISWQM to a large watershed could be costly and difficult.

These significant technical problems for the application of ISWQM are the important areas for further research. More work needs to be directed toward studying the impacts of resource management on natural processes affecting water quality and toward the development of models of these processes. The study and modeling of the impact of stream processes on water quality is also desirable. Model development of stream and physical processes should first concentrate on small watersheds and then be extended to larger watersheds. Research is needed to estimate the water-quality needs for various uses to aid in defining water-quality goals and in estimating benefits and damages. Finally, research should be directed to estimating the damages and benefits associated with water-quality goals.

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Technical difficulties and analytical costs will be greater for an ISWQM approach where a land management plan is developed to meet a set of precisely defined water quality standards than for a simpler ISWQM approach of identifying pollutant priorities and critical source areas. The more sophisticated ISWQM approach will require more costly techniques and, in some cases, more costly data collection. It may also be difficult to find techniques to closely relate land management to water quality parameters.

In summary, ISWQM is a feasible approach to agricultural nonpoint-source pollution control. ISWQM will be more expensive and difficult to apply than source control. ISWQM has the capability, however, to define goals and problems more accurately and plan resource management to control problems more efficiently than source control. If ISWQM is to be applied, the greater analytical and administrative expense and difficulty of applying ISWQM as compared to source control will have to be justified by the more efficient allocation of resources to alleviate water-quality problems than would occur under source control. However, because of relatively high expenses and difficulties of application, a sophisticated ISWQM approach of developing a land management plan to meet a precisely defined set of water quality goals seems most appropriate for waterways with complex management problems or critical values to protect. Other waterways could be managed with a simple ISWQM approach of defining priorities for pollutants and critical source areas or with a source control approach. In some cases, a source control approach might solve water quality problems.

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